Doctoral Dissertation

Influence of weight reduction and increasing physical activity on foot structure and function in Japanese obese adults

Xiaoguang Zhao

Doctoral Program in Sports Medicine

Graduate School of Comprehensive Human Sciences

University of Tsukuba

Contents

Abbreviations

WHO: World Health Organization

QoL: quality of life

PA: physical activity

BMI: body mass index

MTP: metatarsophalangeal

AHI: arch height index

ASI: arch stiffness index

LPA: low physical activity

MPA: moderate physical activity

VPA: vigorous physical activity

MVPA: moderate to vigorous physical activity

METs: metabolic equivalents

3D: three dimensions

kcal: kilocalorie

Chapter 1. General Introduction

The prevalence of obesity has dramatically increased over the past decades. According to the latest statistical data from the World Health Organization (WHO), the worldwide overweight and obese adults have reached more than 1.9 billion in 2014 (WHO 2015). Obesity is generally accompanied by physical inactivity, and has become a global pandemic and recognized as a primary public health concern in many countries. Besides, the large obesity-related health burden negatively affects many relevant health outcomes (e.g. quality of life (QoL), disability, mortality) and results in increased healthcare utilization, thereby rising medical spending (Lehnert et al. 2013).

Obesity is not only a major factor contributing to internal conditions such as cardiovascular diseases, type 2 diabetes, hypertension, certain cancers (Owen et al. 2015, Tanaka et al. 1995), but also has a strong relationship with lower extremity disorders such as osteoarthritis, ankle and foot pain (Frey and Zamora 2007, Ozdemir et al. 2005, Rano et al. 2001). For instance, a recent systematic review investigating 25 papers has noted that obesity is strongly related with non-specific foot pain and chronic plantar heel pain in general population (Butterworth et al. 2012). These lower extremity disorders can substantially lower the QoL, and make the obesity become more severe (Macera 2005).

The human foot, as a complex structure in both physiology and morphology, is considered a miracle of design in engineering and mechanical efficiency (McCarthy and Sperandio 1993). The foot plays an essential role in supporting body weight, maintaining balance and absorbing ground reaction forces generated during activities or sports. Different characteristics of foot structure are commonly accompanied by altering plantar pressure distribution and conditions of the lower extremity bones, muscles, tendons and ligaments, which, in turn, affect lower limb biomechanical characteristics and foot function (Cavanagh et al. 1997, Fan et al. 2011, Kaufman et al. 1999, Rathleff et al. 2014). Understanding the characteristics of foot structure and function may help identify the etiology of some lower extremity disorders.

A possible explanation for the association of obesity with ankle and foot disorders is that excess body weight causes detrimental alterations of foot structure and function (Butterworth et al. 2015). Previous cross-sectional studies have reached a consensus statement that obesity can impact the foot structure. A study measuring dynamic arch index of 81 postmenopausal women exhibited that the excess body weight leads to collapse of the medial longitudinal arch, which adversely affects functional capacity of the foot (Faria et al. 2010). In addition to the arch height, the foot length and width were reported to increase significantly with body weight increased when analyzing relationship between anthropometric foot structure and body weight (Morrison et al. 2007).

On the other hand, excess body weight may lead to the ligament looseness and the muscle strength reduction in ankle joint. It is known that obesity is generally characterized by the higher absolute muscle strength and the lower strength corrected for fat-free mass in knee joint (Hulens et al. 2001). However, in spite of no direct reports to date, indirect evidence may prove that obesity is associated with lowered ankle muscle strength. For instance, it has been shown that obesity has a detrimental impact on balance and ankle instability (Greve et al. 2007, Menegoni et al. 2009), while ankle muscle strength is a strong predictor of the balance and ankle instability (Munn et al. 2003). In combination, there may be an association between obesity and ankle muscle strength.

A correlation may exist between foot structure and ankle muscle strength. From the perspective of kinetic chain, there is a coupling between rearfoot motion and tibial rotation. It has been documented that the navicular height, one assessment of medial longitudinal arch mobility, has relation with calcaneal inversion/eversion (Mathieson et al. 2004). Internal tibial rotation is coupled with eversion/pronation and knee flexion, while external tibial rotation is coupled with inversion/supination and knee extension (Markolf et al. 1976, Pohl and Buckley 2008). Further, a preliminary study has shown a significant correlation between eversion strength and foot arch height in the gymnasts, but no correlation was observed between them in the non-athletic healthy controls (Aydog et al. 2005). Therefore, it is necessary to verify whether a relation exists between foot structure and ankle muscle strength.

Taken together, excess body weight affects kinematics and kinetics, which likely causes changes of foot structure and function. Therefore, for obese individuals, weight reduction and increasing weight bearing physical activity (PA) may be effective approaches to not only decrease the risk of the health-related diseases and improve the QoL (Douketis et al. 2005, Rosemann et al. 2008), but also have positive impact on foot structure and function. As far as the author knows, however, there has been no systematic study on the influence of weight reduction and increasing weight bearing PA on foot structure and function in Japanese obese adults to date.

Therefore, the purpose of this thesis was to investigate the characteristics of foot structure and ankle muscle strength in obese individuals, and find out whether obesity is associated with foot structure and ankle muscle strength. Furthermore, it was determined whether weight reduction and increasing weight bearing PA have positive impact on foot structure and ankle muscle strength.

Chapter 2. Review of Literature

2.1. Anatomy of the Foot

The human foot is composed of 28 bones which located from the rear to the forefoot: talus, calcaneus, navicular, cuboid, 3 cuneiforms, 5 metatarsals, 5 proximal, 4 middle and 5 distal phalanges, one lateral and one medial sesamoid (Figure 2-1). The foot represents a structure which has to adapt to bear body weight, provides balance, assists in mobility, and performs other essential functions (Kitaoka et al. 1994).

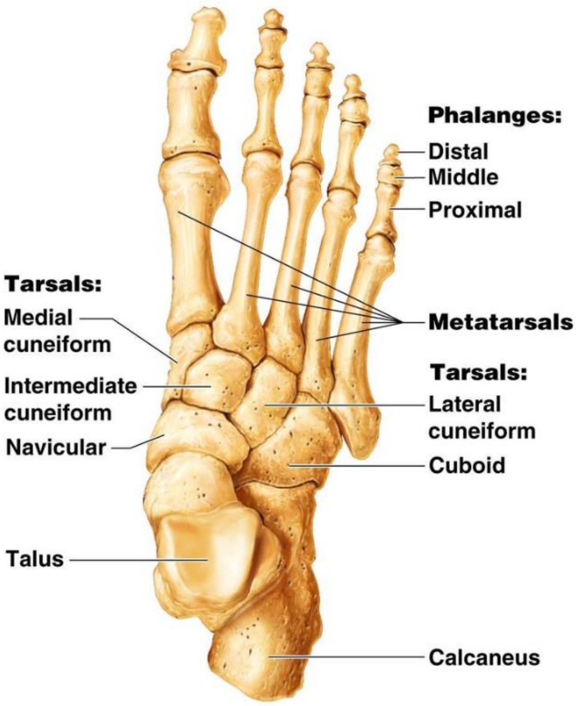


Figure 2-1. Dorsal view of skeleton of the foot

The foot can be subdivided into 3 groups of joints: hindfoot, midfoot, and forefoot. The hindfoot is composed of the talus (or ankle bone) and the calcaneus (or heel bone). The midfoot is connected to the hind- and fore-foot by muscles and the plantar fascia. It includes the 3 cuneiforms, the cuboid and the navicular. The forefoot is composed of the 5 metatarsal bones and the 14 phalanges. The joints between the phalanges are called interphalangeal and those between the metatarsus and phalanges are called metatarsophalangeal (MTP). The major joints in foot and ankle are talocrural joint (ankle joint, tibiotarsal joint), subtalar joint (talocalcaneal joint), talonavicular joint, calcaneocuboid joint, tarsometatarsal joint, metatarsophalangeal joints, interphalangeal joints and metatarsosesamoid joint.

In addition, there are 2 muscular systems: extrinsic and intrinsic. The extrinsic muscles arise from the leg skeleton but their tendons act on the foot. The intrinsic muscles are situated entirely within the foot (Kelly et al. 2014, Kura et al. 1997).

2.2. Medial Longitudinal Arch

The medial longitudinal arch is formed by the calcaneus, the talus, the navicular, the 3 cuneiforms, and the first, second and third metatarsals (Figure 2-2) (Gray 1918). The arch is strengthened by ligaments and tendons, in particular the plantar calcaneonavicular ligament (the spring ligament) and the tibialis posterior tendon

(Kaye and Jahss 1991).

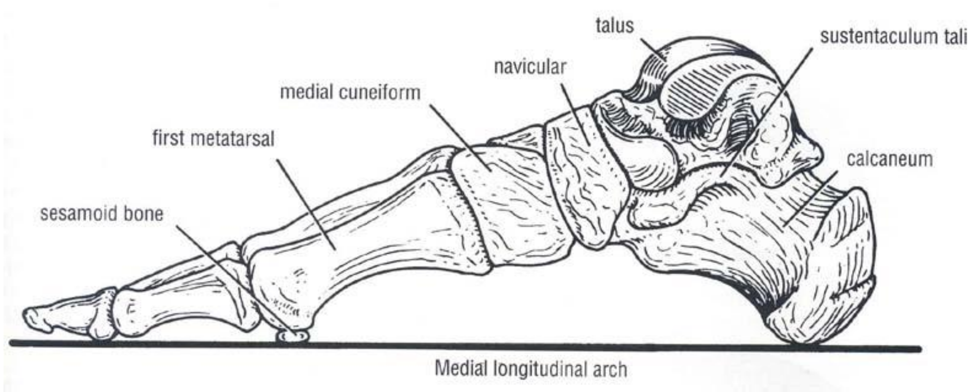


Figure 2-2. Medial view of skeleton of the medial longitudinal arch

The calcaneonavicular ligament is a static support of the head of the talus and a major anatomical contributor to the integrity of the medial longitudinal arch, particularly if the dynamic support of the posterior tibial tendon is compromised (Patil et al. 2007). It is elastic and is thus able to restore the arch to original condition when the disturbing force is removed. Therefore, if the elasticity weakens, it will lower the overall height of the arch. On the other hand, the tibialis posterior tendon is the largest and anteriormost tendon in the medial ankle. It produces plantar flexion and supination of the ankle and stabilizes the plantar vault (Lhoste-Trouilloud 2012). Besides, it is noted that plantar fascia also plays an important role in maintaining arch structure by accounting for approximately 25% of arch stiffness (Kaufman et al. 1999).

The structure of the arch has been reported to be related with the function of the foot (Kaufman et al. 1999, Razeghi and Batt 2002). For instance, one study found that deviations in the normal structure of the medial longitudinal arch cause unstable and unbalanced conditions of the foot such as pes cavus or pes planus (Franco 1987). Moreover, another study proved that the arch height could predict dynamic behavior of the foot during gait (Teyhen et al. 2009).

2.3. Function of the Foot

Human foot is a magnificent architectural and functional design. Since human is able to walk upright, the foot has evolved and developed two main functions to propel body forward efficiently (Bevans 1992). Firstly, the foot has to have sufficient flexibility to adapt to different terrain. Secondly, the foot also has to be a rigid lever which provides strength and power in locomotion. In walking or running, the foot must alternately present as a softer more flexible structure and a strong rigid one. Specifically speaking, the foot needs to be capacity of absorbing the shock of hitting the ground, and then to be firm sufficiently not to collapse when supporting and carrying the body’s weight.

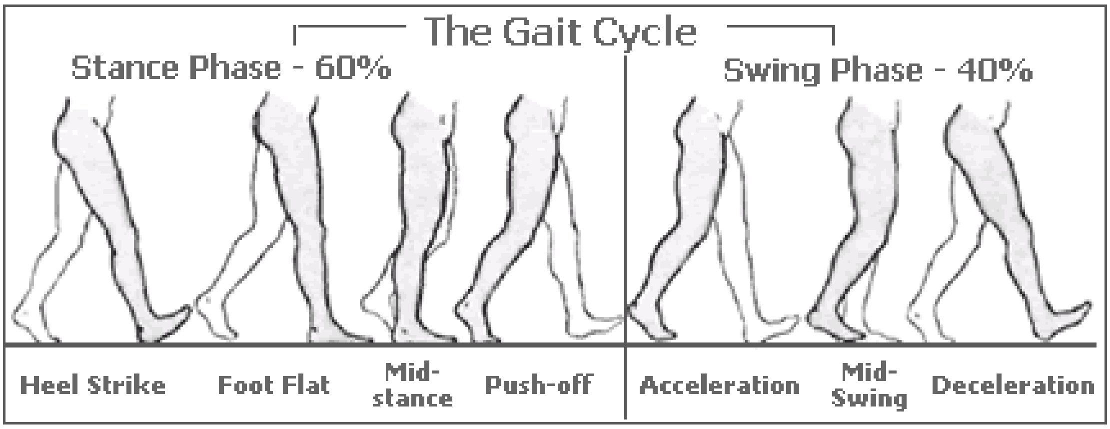


Figure 2-3. The gait cycle

The gait cycle includes two phases: stance phase (weight bearing) and swing phase (non-weight bearing). When walking or running, one gait cycle begins with the heel striking the ground, and ends with the same foot's next heel striking (Figure 2-3). In the gait cycle, the heel strike and push-off are rigid lever, and the foot flat and mid-stance are mobile adapter (Donatelli 1985, Rodgers 1988). In the process of the heel strike and push-off, the muscles and soft tissues are contracted, and the bones and joints of the foot and lower extremity are pulled strongly, which enables the foot to obtain enough force to maintain stability and rigidity. In the process of the foot flat and mid-stance, the muscles and soft tissues are expanded, and the arches are lowered, which enables the force derived from the weight-bearing to be absorbed.

2.4. Foot Structure and Lower Extremity Kinematics and Disorders

According to a report, approximately 60% of the population have normal arches, 20% have cavus feet, and 20% have planus feet (Subotnick 1985). Abnormal foot structure is generally considered as a predisposing factor to lower extremity disorders (Franco 1987). For instance, a study noted that a greater percentage of being injuries and pains in individuals with pes planus than those with normal height of arch (Subotnick 1981). On the other hand, another study indicated that arch height is related with sport-related injuries in US army recruits (Cowan et al. 1993). Moreover, in Israeli female army recruits, it is found that those with lower arches are susceptible to acute and recurrent lateral ankle sprains than those with normal arch height (Mei-Dan et al. 2005). To explain the disorders in lower extremity, several researches have supported the hypothesis that an association exists between arch height and kinematics of lower extremity, especially the rearfoot motion (Hamill et al. 1989, Kernozek and Ricard 1990).

There is an association of foot structure with lower extremity kinematics. Foot structure may contribute to pain or injury through the altered motion of lower extremity. For instance, it has been indicated that individuals with pes panus (flat foot) generally have higher foot mobility than those with pes cavus (higher arch) (Barnes et al. 2008, Kaufman et al. 1999), which leads to a greater risk of tissue stress injuries by reason of abnormal joint rotation or joint coupling (Nawoczenski et al. 1998, Nigg et al. 1993). On the contrary, individuals with pes cavus are more likely to have less foot mobility, which also leads to a greater risk of injuries associated with increased peak plantar pressures or decreased shock attenuation (Burns et al. 2005, Williams et al. 2001).

Specifically speaking, when walking or running, enhancing pes cavus is generally related with increased peak eversion and range of motion of rearfoot during the stance phase of gait, particularly when rearfoot rise during the propulsive phase of gait (Buldt et al. 2013). When come to the motion of foot, the relationship is mostly found in the frontal plane (Cobb et al. 2009, Powell et al. 2011). Furthermore, the forefoot and midfoot show prolonged and increased transverse plane motion in the pes planus than the normal foot (Hunt and Smith 2004). It is suggested that there is an association between pes planus and increased frontal plane motion of rearfoot. However, the relationship does not mean causation between them. Other factors which are responsible for both foot structure and lower extremity kinematics may exist.

Foot structure also has a relationship with balance and function ability, especially for older adults. Menz et al (2005) reported that foot and ankle structural characteristics, together with strength of foot could significantly predict balance and functional ability of older individuals. Similarly, Spink et al (2011) also observed that foot and ankle structural characteristics, particularly plantar flexion strength of the hallux and range of motion of ankle inversion-eversion, are significant predictors of balance and functional ability in older people.

2.5. Influence Factors of Foot Structure

2.5.1. Gender

Foot structure is differences in genders. It has been documented that men generally have a longer, higher and broader foot than women. Paiva de Castro et al (2011) investigated older Brazilians using calipers and footprints, and reported that the instep height and forefoot and rearfoot width were significantly lower in women than in men. Furthermore, using a 3D foot scanner that measured 291 older adults, more recent investigators reported that older men had significantly greater values for all dimensions than women with the exception of the first toe angle, which was smaller in men (Saghazadeh et al. 2015).

Moreover, previous studies also have noted gender differences in the properties and alignment of the lower extremity musculoskeletal system (Horton and Hall 1989, Wunderlich and Cavanagh 2001). Rozzi et al (1999) indicated that women are more likely to have more ligamentous laxity. Further, several previous studies noted that women also have a greater tendency toward knee valgus compared with men when active loading (Ferber et al. 2003, Malinzak et al. 2001). Because of the coupling of motions of knee and foot, this may result in a tendency for increased foot pronation, which is often related to a low-arched foot (Hintermann et al. 1994, Stacoff et al. 2000). However, a report noted that there was no significant difference in the dorsal arch height between young men and women military recruits (Wunderlich and Cavanagh 2001). But, the report did not show the age group of subjects. It may be possible that foot structure of young men and women military recruits is homogenous.

2.5.2. Age

Age also may be an influence factor of foot structure. Researchers have noted that when individuals are in their fifth and sixth decades of life, a greater number of them had flat feet (Funk et al. 1986, Mann and Inman 1964). For instance, one previous study stated that older adults (80.2 ± 5.7 years) exhibited a trend toward flatter feet than younger adults (20.9 ± 2.6 years) using the arch index (the arch index was calculated by dividing the narrowest part of the midfoot by the widest part of the forefoot) (Scott et al. 2007). Moreover, Tomassoni et al (2014) divided age into the young (20-25 years), adult (35-55 years) and old (65-70 years) males and indicated that foot circumferences were most influenced by age-related differences.

It is known that ageing is generally accompanied by loss of bone and muscle mass, and reduction of strength (e.g. sarcopenia and osteoporosis) (Burr 1997), which lead to the different characteristics of foot structure. Prince et al (1997) have been confirmed that the soft tissue in foot and ankle tends to stiffen and osteophytes form with ageing. These changes can also result in limitations in joint motion of lower extremity.

2.5.3. Obesity

A large number of previous studies have been noted that there is an association between obesity and foot structure. A study of 100 obese and 84 non-obese participants found that those with obesity demonstrated greater forefoot width and lower arch height than non-obese counterparties, and BMI is correlated with measures of foot structure in the obese participants (Güven et al. 2009). Similarly, Aurichio et al (2011) investigated 399 participants and indicated that obese women generally presented with flatter feet and obese men always presented more pronated feet. In an another study of investigating the influence of BMI on arch structure, Wearing et al (2012) utilizing multiple regression analysis finding that BMI is a significant predictor of footprint-based measures of arch height. Moreover, Wearing et al (2004) measured body composition of 24 participants, finding that fat-free mass was significantly associated with the contact area of the forefoot and rearfoot, while fat mass was remarkably related to the midfoot contact area.

As to the relationship between obesity and dynamic arch structure, Faria et al

(2010) investigated 81 postmenopausal women and indicated there was a significant association between obesity and pronated dynamic arch structure. A similar study analyzed foot structure of 239 women and noted that those with obesity had remarkably foot abduction and rearfoot eversion than non-obese individuals (Messier et al. 1994). In addition, obese participants were found to have significantly worse balance during gait, and foot abduction also was observed in obese individuals (Sarkar et al. 2011).

The greater mechanical loading of the lower extremity (when walking and jogging) may be one possible explanation for the relationship between obesity and abnormal foot structure. Moreover, decreased postural stability and increased leg swing velocity have been found in obese individuals (Błaszczyk et al. 2010, Rein et al. 2010) , which may also result in alterations of foot structure and function.

2.5.4. Muscle Strength

The foot and ankle muscles are a powerful guarantee that generates force for postural control and keeping balance during locomotion. Because many physical activities or exercises are performed in a standing position, the foot arch plays an important role in reducing the impact forces on the load during walking and running movements. It has been indicated by foot and ankle specialists that a main factor which affects development and progression of flat foot deformities is the weakness of the foot and ankle muscles, including the triceps surae, tibialis anterior, extensor digitorum longus and extensor hallucis longus muscles (Brodersen et al. 1993, Kulig et al. 2005, Takao et al. 2007, Villarroya et al. 2009).

Increasing weight bearing PA or muscle strength training may have an impact on the foot structure and function. Hashimoto and Sakuraba (2014) suggested that arch maintenance function was improved along with enhanced intrinsic foot flexor strength after strength training. Fukuda and Kobayashi (2008) showed that forefoot arch maintenance is associated with the intrinsic foot muscles. Furthermore, in the interventional study, Umeki (1991) reported that during 1-legged standing, the foot arches were shortened by intrinsic and extrinsic foot muscle contraction, which may protect the plantar support ligaments and joint tissue. Mulligan and Cook (2013) used Short Foot Exercise to enhance arch height for 8 weeks, finding that this method is effective to increase arch height and improve functional balance.

2.5.5. Bilateral Symmetry

Due to the existence of lateral dominance, bilateral asymmetry becomes a common phenomenon in anatomical structures (Keles et al. 1997, Plato et al. 1980). Dominance is defined as the demonstration of a preference to perform or complete a task with the left or right side. Purves et al (1994) reported that right-dominant participants had remarkably larger right hands, which may be evolved from the different functional demands related to dominance. These differences also exist in the foot and may impact its structure. A research from Zifchock et al (2006) provides evidence for the relationship between foot dominance and arch structure, indicating that the arch height of the dominant foot was significantly greater than that of the non-dominant foot.

2.5.6. Others

Besides influence factors mentioned above, other influence factors such as genetic factors and wearing shoes habit are also considered to affect foot structure and function (Chuckpaiwong et al. 2008, Suzuki and Ando 2014). For instance, Miller et al (2014) and Snow et al (1992) noted that wearing minimal or high heeled shoes is more likely to develop lower arch and greater hallux valgus, and induces higher demands on intrinsic muscles which support the arch when performing weight bearing exercise.

2.6. Summary

Collectively, the human foot is a complex structure in both anatomy and physiology. The foot plays an important role in supporting body weight, maintaining balance and absorbing ground reaction forces generated during gait. The changes of foot structure are generally accompanied by altering conditions of bones, muscles, tendons and ligaments around foot and ankle, which in turn affect lower limb biomechanical characteristics and foot function, even leading to pain and injuries. Influence factors of foot structure can be classified by two types. The first type is uncontrollable factors such as gene, gender and age, while the anther type is controllable factors that include obesity and physical activities. However, changing controllable factors of foot structure such as obesity or physical activities may have a beneficial impact on foot structure and function, and then enhance and improve foot and ankle health.

Chapter 3. Purposes and Main Studies of Thesis

The purposes of this thesis were to investigate the association of obesity with foot structure and ankle muscle strength, and to determine whether weight reduction or increasing weight bearing PA has a positive impact on foot structure and ankle muscle strength. In order to fulfill the above purposes, this thesis was divided into several parts as follows:

Study 1. Association of obesity with foot structure and ankle muscle strength

1.1. Characteristics of foot structure and their relations to gender, age, obesity and bilateral asymmetry

The purpose of this study was to investigate the characteristics of foot structure, and find out what impacts do factors such as gender, age, obesity and bilateral asymmetry have on foot structure in healthy adults.

1.2. Association of obesity with ankle muscle strength

The objective of this study was to determine whether obesity has an impact on ankle muscle strength. Both BMI and body fat percentage were employed to assess obesity, and verify their association with ankle muscle strength in male obese and non-obese adults.

Study 2. Weight reduction or increasing PA on foot structure and function

2.1. Influence of weight reduction on foot structure and ankle muscle strength

The aim of this study was to explore whether the weight reduction induced by 12-week dietary improvement has an influence on both foot structure and ankle muscle strength in obese adults.

2.2. Influence of increasing weight bearing PA on foot structure and ankle muscle strength

The purpose of this study was to examine whether the 12-week increasing weight bearing PA intervention has an impact on both foot structure and ankle muscle strength in obese adults.

Chapter 4. Materials and Methods

4.1. Participants

All participants in this study were recruited through advertising in local newspapers in Tsukuba City, Ibaraki Prefecture, and Ise City, Mie Prefecture, Japan in 2014 and 2015. A total of 180 participants, 101 men and 79 women, with an age range of 30 to 82 years, volunteered for this study. All of them had no habit of regular exercise (less than 150 minutes per week), and had no current or previous foot pain, foot surgery and other neuromuscular or musculoskeletal disorders that affect foot and ankle health. Prior to the start of the tests, the participants were asked to read and sign a written informed consent form. This study was approved by the Human Ethics Board of the University of Tsukuba which complied with the Helsinki Declaration.

4.2. Anthropometric Variables

Body height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (YG-200; Yagami, Nagoya, Japan). Body mass was assessed to the nearest 0.1 kg using a digital scale (TBF-551; Tanita, Tokyo, Japan) as the participants wore light clothing and no shoes. BMI was computed as the body mass (kg) divided by body height squared (m^2). Obesity (BMI > 25 kg/m^2) was determined according to cut-off values developed by the Japan Society for the Study of Obesity. Then, body composition was measured using a hand-to-hand bioelectrical impedance (HBI-354, Omron Healthcare Inc., Kyoto, Japan) by trained technicians. Body fat percentage was calculated as fat mass (kg) divided by body weight (kg).

4.3. Foot Structure Measurements

A 3 dimensions (3D) leaser foot scanner (FSN-2100, Dream GP Inc., Osaka, Japan) was employed to measure foot structure information (Figure 4-1). The 3-dimension surface scanning system has been recommended for collecting foot anthropometric data because it has relatively higher precision and accuracy comparing to conventional measurement methods (ICCs: from 0.94 to 0.99) (Lee et al. 2014). In this research, both the left and right foot anthropometric data were measured for each participant in both the sitting and bipedal standing positions with bare feet.

The procedures for measuring foot anthropometric data were as follows. First, the participants were asked to sit on a chair with bare feet, and were instructed to place the right foot on a specified location inside the foot scanner. To prevent ankle plantarflexion or dorsiflexion, the participants were taught to keep the lower shank perpendicular to both the thigh and floor, with their hands at their sides. Next, an opaque material attached to the frame of the scanner was secured to the participants' lower shank in order to prevent light from escaping from the scanner. When the tests were started, a laser rotated on the rail around the foot computed approximately 30,000 points, including the instep, heel, sole and toe, allowing the software to rebuild the exact shape of the foot on the computer. Each measurement was completed about in 13 seconds. Once a sitting position measurement was completed, the participants were required to stand up without changing the position of the right foot as much as possible, which remained inside the foot scanner. They were kept upright, looking straight ahead, with their hands placed down at their sides and their body weight spread equally on both feet when the test was started. The same procedure was performed to obtain data from the left foot. After finishing each test, 70% alcohol was used to sanitize the glass pedal of the foot scanner prior to measuring the next participant.

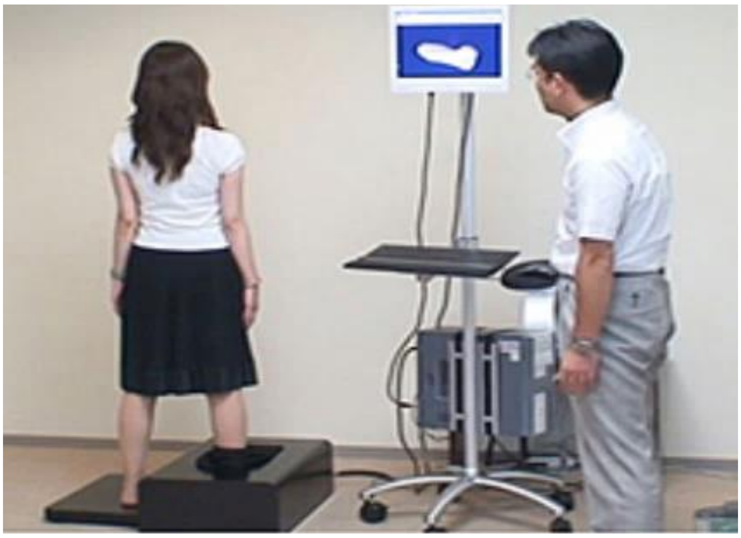


Figure 4-1. The 3D foot scanner for measuring foot structure.

Foot structure indicators were obtained automatically using the 3D foot scanner analysis software (Figure 4-2). The descriptions of the major indicators of the foot structure are shown as follows.

1) Foot length: the most posterior point of the calcaneus to the anterior point of the most protruding toe.

2) Forefoot width: the distance between the ball of the first and fifth metatarsophalangeal joint.

3) Forefoot girth: the circumference over the first and fifth metatarsophalangeal joint.

4) Rearfoot width: the widest section of the heel (calcaneus).

5) Ball of foot length: the most posterior point of the calcaneus to the ball of first metatarsophalangeal joint.

6) Lateral ball of foot length: the most posterior point of the calcaneus to the ball of fifth metatarsophalangeal joint.

7) Instep height: the highest point at the longitudinal section of 55 % foot length.

8) Instep girth: the circumference of the longitudinal section of 55 % foot length.

9) First toe angle: the angle between the big toe and the ball of the first metatarsophalangeal joint.

10) Little toe angle: the angle between the little toe and the ball of the fifth metatarsophalangeal joint.

11) Arch height index (AHI): instep height/ball of foot length.

12) Arch stiffness index (ASI): AHI (standing) / AHI (sitting).

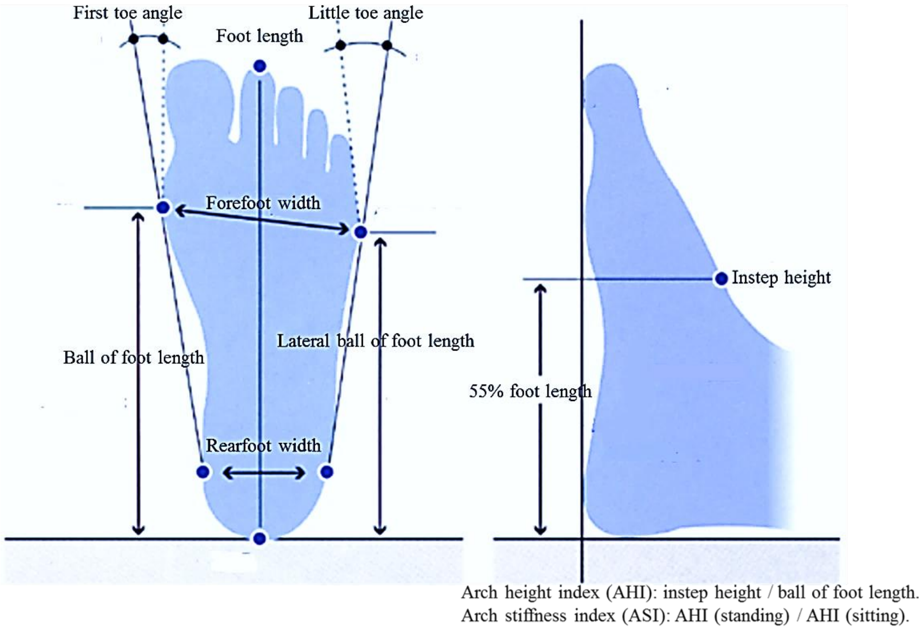


Figure 4-2. The descriptions of the major indicators of foot structure.

Among the many indicators of foot structure mentioned above, both AHI and ASI are comprehensive indicators for assessing the arch and foot. The AHI was defined as the instep height divided by the ball of the foot length, which was introduced by Williams and McClay (2000) to evaluate the arch height. The ASI was developed by Richards et al (2003) to assess arch flexibility and was defined as the ratio of the standing AHI divided by the sitting AHI. A value for AHI close to 0 represents a lower arch, and a value for ASI close to 1 represents a stiffer arch.

4.4. Ankle Muscle Strength Measurements

A Biodex System 4 Dynamometer with Biodex Advantage Software Package (Biodex Medical System Inc., Shirley, NY, USA) was employed to measure peak torque and peak torque per body weight in right ankle (Figure 4-3). Plantarflexion and dorsiflexion, eversion and inversion were measured at a speed of 30 degrees/second angular velocity. Selecting such slow velocity was not only because it is frequently used in previous studies, but also because high velocity has potential risk of injuries and very hard to perform when testing ankle muscle strength (Willems et al. 2002).

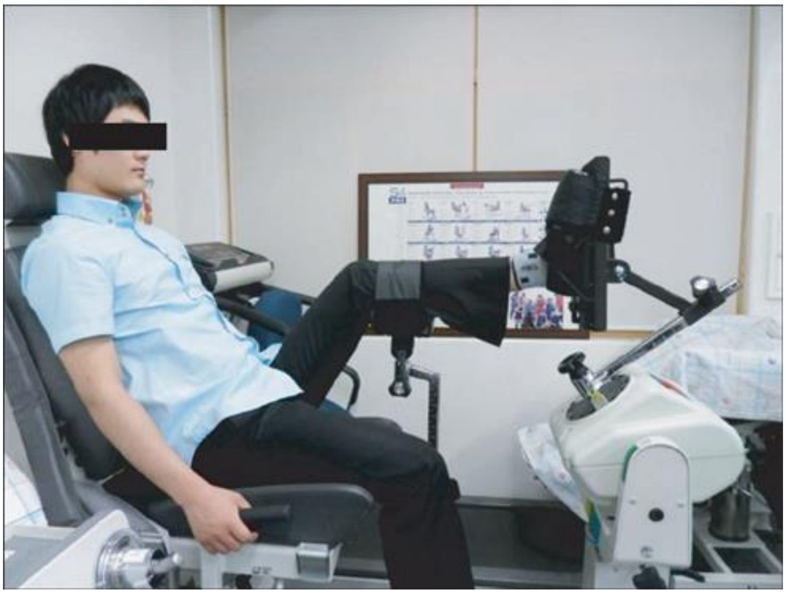


Figure 4-3. The Biodex Dynamometer for testing ankle muscle strength

Before the test, 2 to 3 minutes' warm-up exercise mainly aiming at the ankle joint was performed with an experienced staff for each participant. At the same time, isokinetic dynamometer was set and positioned in accordance with the manufacturer's recommendations. Then participant seated on the Biodex chair with two straps stabilized the trunk and the hip. For each participant, dynamometer, knee pad and positioning chair were adjusted to align the midline of the foot with the midline of the patella, and ensure that the lower shank was parallel to the floor. The dynamometer orientation, tile, and seat orientation were kept at 90, 0, 90 degrees during plantarflexion to dorsiflexion test, and at 0, 70, 90 degrees during eversion to inversion test. A range of motion was used to determine start and stop angles for each participant based on each participant's active range of motion. After an explanation of the testing procedure to participants, 1 submaximal repetition was given in order to become familiar with the testing procedure, then a test consisted of 3 maximal repetitions at a speed of 30 degrees/second for plantarflexion to dorsiflexion and eversion to inversion was performed respectively. During the testing procedure, verbal encouragement was consistently given to each participant.

The highest muscular force output at any moment during a repetition was defined as peak torque (Nm), and peak torque per body weight (Nm/kg*100%). In order to reduce the test error, all measurements were completed by the same tester.

4.5. Weight Reduction Intervention

Weight reduction intervention was mainly composed by dietary modification sessions (1 time per week, 90 minutes per session), through which participants were instructed to how to restrict their energy intake scientifically and effectively to approximately 1680 kcal/day for men and 1200 kcal/day for women (Tanaka et al. 2004) using Four-Food-Group Point Method (Figure 4-4). In the Four-Food-Group Point Method, diet is divided into 4 food groups based on nutrient content as follows: group 1 (dairy products and eggs), group 2 (beans, fish and meat), group 3 (fruits and vegetables) and group 4 (sugar, oils and grains). The purpose of dietary modification sessions was to help participants obtain a nutritionally well-balanced diet daily based on the Smart Diet which was used for more than 20 years by our laboratory. During the 12-week weight reduction program, each participant was required to record a detailed daily diary in which every food they ate must be weighed and then transformed into energy. The daily diary could be checked seriously and added some private advice and encouraging words by experienced staffs. According to the past experiences for many years, the Smart Diet has been proven to be safe and very effective in reducing weight while forming healthy dietary habits. More detailed information about the Smart Diet has been published previously by our laboratory (Matsuo et al. 2010).

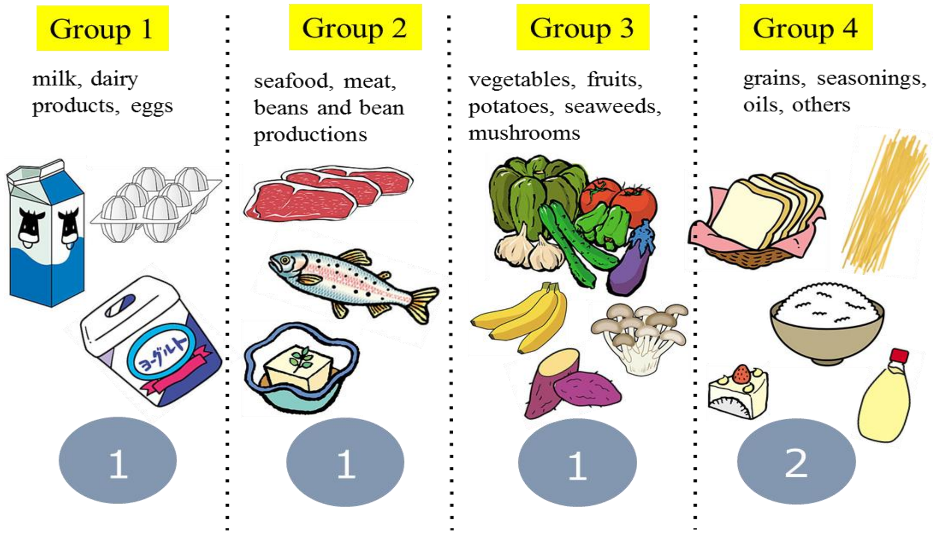


Figure 4-4. The Smart Diet

4.6. Increasing Physical Activity Intervention

During the PA intervention, participants came to the Fitness Room at University of Tsukuba three times a week for a 90-min increasing weight bearing PA session for 12 weeks. The purpose of the session was to help participants increase their PA. Each PA session was mainly composed by a 15-min warm-up and stretching, a 60-min brisk walking and jogging, and followed by a 15-min cool-down and stretching (Figure 4-5). At the first 4 weeks, the exercise intensity was set at 50-60% of maximal heart rate (220 – Age), and gradually increased afterwards. The participants finally were exercising at 60-70% of maximal heart rate at the last 4 weeks. On rainy days, indoor exercise was carried out using stationary cycling or stair-stepping. Several experienced exercise instructors and principal investigators were responsible for the increasing PA intervention program. In addition to the exercise in the PA session, participants were also encouraged to conduct their preferred type of PA at home or workplace as much as possible.

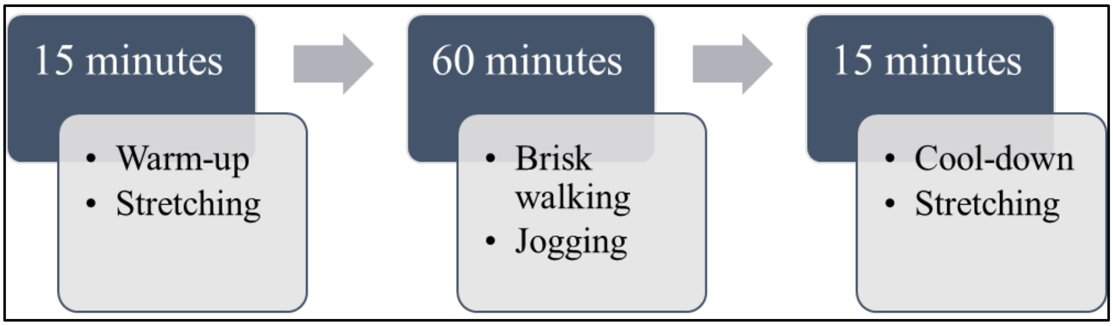


Figure 4-5. The increasing PA intervention

Chapter 5 (Study 1.1). Characteristics of Foot Structure and Their Relations to Gender, Age, Obesity and Bilateral Asymmetry

5.1. Introduction

The human foot, as a complex structure in both physiology and morphology, is considered a miracle of design in engineering and mechanical efficiency (McCarthy and Sperandio 1993). The foot plays an essential role in supporting body weight, maintaining balance and absorbing ground reaction forces generated during activities or sports. Different characteristics of foot structure are commonly accompanied by altering plantar pressure distribution and conditions of the lower extremity bones, muscles, tendons and ligaments, which, in turn, affect lower limb biomechanical characteristics and foot function (Cavanagh et al. 1997, Fan et al. 2011, Kaufman et al. 1999, Rathleff et al. 2014). Therefore, clarifying which factors impact foot structure is helpful in understanding the basis of foot deformity and foot dysfunction and in designing more comfortable footwear.

Certain factors such as gender, age, BMI and bilateral asymmetry may influence foot structure to some extent. Restricted from the technique, almost all previous studies have focused on arch height and hallux valgus using calipers, footprint parameters and radiographic evaluation (Aurichio et al. 2011, Nix et al. 2010, Wunderlich and Cavanagh 2001, Zifchock et al. 2006).

The emergence and improvement of 3D imaging technology make the accurate measurement of foot structure (length, width, height and girth) become possible (Telfer and Woodburn 2010). However, to the best of our knowledge, only one study has directly demonstrated how gender influences foot structure in older Japanese adults using a 3D foot scanner (Saghazadeh et al. 2015). The authors reported that gender differences were primarily in the instep height, instep girth, forefoot girth and navicular height by measuring the foot information of 151 men (74.5 ± 5.6 years) and 140 women (73.95 ± 5.1 years). According to their findings, the authors appealed to shoe manufacturers to consider gender differences when designing shoes for older adults.

Although arch type and hallux valgus have been reported to be associated with gender, age, body composition and bilateral asymmetry, to date, detailed systematic studies are rare regarding foot structure characteristics in different Japanese adult groups. Therefore, the purpose of this study was to investigate the influence of gender, age, BMI and bilateral asymmetry on a range of foot structure characteristics in a large community sample of Japanese adults.

5.2. Materials and Methods

Participants

A total of 180 participants, 101 men and 79 women, with an age range of 30 to 82 years, participated in this cross-sectional study. All of them had no exercise habits and volunteered for this study. Participants were recruited through advertising in local newspapers in Tsukuba City and Ise City, Japan in 2015. Prior to the start of the tests, the participants were asked to read and sign a written informed consent form. This study was approved by the Human Ethics board of the University of Tsukuba.

Anthropometry

All the anthropometric items have been described in Chapter 4.

Foot Anthropometric Measurement

The foot anthropometric measurement has been described in Chapter 4.

Statistical Analysis

Except for bilateral asymmetric analysis, only right foot structure information was analyzed to satisfy the independence of assumption of the statistical analysis (Menz 2004). Because the foot structure indicators were observed to be normally distributed using the Shapiro-Wilks test, independent samples t-test was used to determine the gender differences. If gender differences were observed, ANCOVA was used to remove compounding variables such as age and BMI. Both the age and BMI were divided into three groups according to the domestic standards, and one-way ANOVA with the Bonferroni post hoc test was employed to examine the age and BMI differences in foot structure. Then, ANCOVA was executed to adjust for gender, age or BMI if differences were found. We applied paired samples t-test to detect bilateral asymmetry in the left and right foot structure. Finally, multiple linear regression models were employed using a range of foot structure indicators as dependent variables, and taking gender, age and BMI as independent variables.

In all data analyses, a P-value less than 0.05 was considered to be statistically significant. The data were analyzed using IBM Statistical Package for Social Sciences (SPSS) version 22.0.

5.3. Results

The anthropometric characteristics of all 180 participants are shown in Table 5-1. Figure 5-1 exhibits the gender differences in foot structure. Except for the little toe angle and ASI, there were very significant gender differences in foot structure indicators. Compared with females, males had longer feet (foot length, ball of foot length, and lateral ball of length; all $P < 0.001$), larger feet (forefoot girth and width, rearfoot width, and instep girth; all $P < 0.001$), higher arches and feet (AHI and instep height; both $P < 0.001$), and smaller first toe angles ($P = 0.002$). Although compounding factors such as age and BMI were adjusted using ANCOVA, we only found that the first toe angle difference ($P = 0.087$) disappeared between genders.

The age differences in foot structure are shown in Figure 5-2. Most of the foot structure indicators, apart from the little toe angle and AHI, had significant differences among prime-aged, middle-aged and older adults. The feet in older adults became shorter (foot length, ball of foot length, and lateral ball of length; all $P < 0.001$), narrower (forefoot girth and width, rearfoot width, and instep girth; all $P < 0.001$), and lower (instep height; $P < 0.001$). Furthermore, older individuals were more likely to have a larger first toe angle ($P = 0.001$) and stiffer arch (ASI; $P = 0.011$). However, when gender and BMI were considered, there were no age differences in the forefoot girth, forefoot width, rearfoot width, instep height and girth, and first toe angle.

Except for the first toe angle, little toe angle and ASI, significant differences were found among the three BMI groups in Figure 5-3. Compared with the non-obese adults, the feet in overweight and obese individuals were longer (foot length, ball of foot length, and lateral ball of length; all $P < 0.001$), larger (forefoot girth and width, rearfoot width, and instep girth; all $P < 0.001$), and higher (instep height; $P < 0.001$). Moreover, adults with higher BMI had a higher arch than those with lower BMI (AHI; $P = 0.008$). When confounding factors such as gender and age were considered, we still found BMI differences in width, circumference and height parameters such as forefoot girth and width, rearfoot width, instep girth and height and AHI.

Regarding the bilateral asymmetry, the instep height and AHI were different (Figure 5-4). We observed that the right arch and foot were higher (instep height, $P = 0.001$; AHI, $P = 0.001$) than the left arch and foot. In addition, there was no other difference between the left and right foot.

Multiple linear regression models exhibiting gender, age and BMI can account for 37% to 71% of the variation in the forefoot width, rearfoot width, instep height, foot length, forefoot girth, ball of foot length, lateral ball of foot length and instep girth (Table 5-2). Age could significantly predict the foot length, forefoot girth, ball of foot length, lateral ball of length and instep girth ($\beta = -0.23$ to -0.10, all $P < 0.05$). Both gender and BMI were significant predictors of the foot length, forefoot girth and width, rearfoot width, ball of foot length and lateral ball of foot length, instep height and girth ($\beta = 0.43$ to 0.59, all $P < 0.001$ for gender; $\beta = 0.16$ to 0.39, all $P < 0.01$ for BMI). In addition, BMI could also remarkably predict AHI ($\beta = 0.23$, $P < 0.003$) and ASI ($\beta = -0.19$, $P = 0.020$).

5.4. Discussion

The purpose of this study was to determine characteristics of foot structure and whether gender, age, BMI and bilateral asymmetry impact a range of foot structure indicators. The results demonstrate that males generally had longer, larger and higher feet; the feet in older individuals were shorter and stiffer; the value of height and width indicators of foot in those with higher BMI was larger, and the value of height of arch was also larger; the right foot had a higher foot and arch than the left foot. Gender, age and BMI could impact length and girth indicators of foot together.

The gender differences in foot structure reported here are consistent with those in previous studies, indicating that men had longer, higher and larger feet than women. Paiva de Castro et al (2011) investigated older Brazilians using calipers and footprints, reporting that the instep height and forefoot and rearfoot width were significantly lower in women than in men. Furthermore, using a 3D foot scanner that measured 291 older adults, more recent investigators reported that older men had significantly greater values for all dimensions than women with the exception of the first toe angle, which was smaller in men (Saghazadeh et al. 2015). We obtained similar results in our study, indicating that men had longer, higher and larger feet than women, even when compounding factors such as age and BMI were adjusted. However, regarding the first toe angle, the gender difference disappeared when considering compounding factors. Smaller body size in women may lead to the shorter, lower and narrower foot than that in men. Additionally, compared to men, women generally have more internal valgus knees and more pronated ankles (Kernozek et al. 2005), which may induce a lower arch in women.

Concerning the relationship between age and arch structure, one previous study stated that older adults exhibited a trend toward flatter feet than younger adults using the arch index (the arch index was calculated by dividing the narrowest part of the midfoot by the widest part of the forefoot) (Scott et al. 2007). However, another study, defining the AHI similar to ours, found that no statistically significant relationship was observed between increased age and AHI (Zifchock et al. 2006). Our research supported the latter statement. It is very likely because we used the same determination method for assessing arch. Regarding foot structure, to the best of our knowledge, only one study has investigated the relationship between age and foot structure. Tomassoni et al (2014) divided age into the young (20-25 years), adult (35-55 years) and old (65-70 years) males and indicated that foot circumferences were most influenced by age-related differences. Although the division of age was different, our results showed that age differences were not only found in foot circumferences but also in other foot structures such as the foot length and arch stiffness. Even when gender and BMI were considered, the foot length, ball of foot length and arch stiffness were still associated with ageing. One possible explanation may be that ageing is generally accompanied by loss of bone and muscle mass, and reduction of strength (e.g. sarcopenia and osteoporosis) (Burr 1997), which lead to the different characteristics of foot structure.

Several previous studies have indicated that being overweight and obese negatively influence foot structure and function in both children and adults (Butterworth et al. 2015, Dowling et al. 2001, Riddiford-Harland et al. 2000). The Mauch research group (2008) showed that overweight children more commonly had flat and robust feet than underweight children. Moreover, the prevalence of flat feet in overweight or obese children was 1.39 and 2.66 times greater than that in non-obese children (Chang et al. 2010). Similar to the result in children, the association between flat feet and obesity was also found in adult Australians and Americans (Butterworth et al. 2015, Gill et al. 2014). However, Atamturk (2009) stated that there were no associations between the presence of flat feet or a high arch and body weight or BMI in Turkish individuals. In the present study, AHI, which assesses arch height, was found to be higher in those with greater BMI. The appearance of such results may be related to higher and larger feet. The values of higher and larger foot indicators, such as forefoot girth, forefoot width, rearfoot width, instep height and instep girth, were significantly greater in those with higher BMI.

Bilateral asymmetry is a common phenomenon in other anatomical structures (Keles et al. 1997, Plato et al. 1980). The present study investigated the difference in foot structure between the left and right foot across all participants. The results exhibited that the left foot had a larger ball of foot length, a lower instep height and AHI than the right foot, indicating that the right foot had a higher arch and foot than the left foot. The reason for this result may stem from foot dominant because the overwhelming majority of the population is right foot dominant. A research from Zifchock et al (2006) provides evidence for our assumption, and they noted that the arch height of the dominant foot was significantly greater than that of the non-dominant foot. In light of these results, it is indicated that bilateral asymmetry of the foot can affect the height of the arch and foot.

Theoretically, the development of certain foot structure should be influenced to some extent by several related factors together. Although gender, age and BMI have been documented separately to affect foot and arch structure in previous studies (Aurichio et al. 2011, Nix et al. 2010, Wunderlich and Cavanagh 2001, Zifchock et al. 2006), there are few papers which studied the combined effect of these three factors on foot structure. In our study, we found that gender, age and BMI could impact length and girth indicators of foot together, and could explain 37-71% of the variation. In them, gender was a bigger predictor of the length, width, height and girth indicators of foot ($\beta = 0.43$ to 0.59, all $P < 0.001$) than age or BMI. As to the arch, BMI was a significant predictor of AHI ($\beta = 0.23$, $P = 0.003$) and ASI ($\beta = -0.19$, $P = 0.020$).

Similar to our findings, a research also found that BMI could predict arch height in adults ($\beta = 0.39$, $P = 0.04$) (Wearing et al. 2012). Based on these findings, BMI seems to be one of the most important factors that affect the foot arch.

5.5. Conclusion

In summary, this study showed that the development of foot structure is a result of combined effect of several related factors such gender, age and BMI. In them, gender has a greater impact on length, width, height and girth indicators of foot than age or BMI. Compared BMI with age, BMI has a more influence on width, height and girth indicators of foot, while age has a more effect on length indicators of foot. BMI also has an impact on both AHI and ASI. Additionally, bilateral asymmetry affects values of height indicators of foot and arch.

Table 5-1. Characteristics of the study participants.

	Prime-aged adults (25-44 years)		Middle-aged adults (45-64 years)		Older adults (more than 64 years)		Total = 180	
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Number (women)	23 (10)	—	98 (41)	—	59 (28)	—	180 (79)	—
Age (years)	37.39	4.25	55.00	5.84	70.76	3.90	57.92	11.78
Height (cm)	171.78	5.98	165.60	9.00	156.40	8.01	163.37	9.84
Weight (kg)	89.49	27.63	71.12	14.14	56.04	9.73	68.52	18.56
BMI (kg/m^2)	30.25	8.95	25.79	3.94	22.80	2.83	25.38	5.12

Table 5-2. Multiple linear regression analysis using foot morphology parameters as dependent variables respectively, and age, gender and BMI as independent variables.

Variables		B	SE (B)	β	t	P	R^2
Foot length (mm)	gender	16.54	1.75	0.53	9.48	< 0.001	
	age	-0.30	0.08	-0.23	-3.97	< 0.001	0.55
	BMI	0.50	0.17	0.17	2.99	0.003	
Forefoot girth (mm)	gender	14.59	1.70	0.49	8.59	< 0.001	
	age	-0.15	0.07	-0.12	-2.04	0.042	0.55
	BMI	1.01	0.16	0.35	6.24	< 0.001	
Forefoot width (mm)	gender	5.61	0.87	0.43	6.48	< 0.001	
	age	-0.06	0.04	-0.11	-1.57	0.119	0.37
	BMI	0.30	0.08	0.23	3.56	< 0.001	
Rearfoot width (mm)	gender	4.51	0.59	0.45	7.69	< 0.001	
	age	-0.04	0.03	-0.08	-1.40	0.164	0.52
	BMI	0.38	0.06	0.39	6.79	< 0.001	
Ball of foot length (mm)	gender	12.48	1.26	0.55	9.90	< 0.001	
	age	-0.22	0.06	-0.23	-3.99	< 0.001	0.57
	BMI	0.36	0.12	0.16	2.94	0.004	
Lateral ball of foot length (mm)	gender	11.10	1.11	0.55	9.99	< 0.001	
	age	-0.19	0.05	-0.22	-3.87	< 0.001	0.57
	BMI	0.32	0.11	0.17	3.03	0.003	
Instep height (mm)	gender	6.76	0.70	0.56	9.68	< 0.001	
	age	-0.01	0.03	-0.02	-0.37	0.714	0.53
	BMI	0.35	0.07	0.30	5.27	< 0.001	
Instep girth (mm)	gender	20.83	1.63	0.59	12.79	< 0.001	
	age	-0.15	0.07	-0.10	-2.16	0.032	0.71
	BMI	1.30	0.16	0.38	8.35	< 0.001	
First toe angle (degree)	gender	-1.95	1.13	-0.14	-1.72	0.087	
	age	0.09	0.05	0.15	1.83	0.069	0.09
	BMI	-0.12	0.11	-0.09	-1.09	0.277	
Little toe angle (degree)	gender	0.59	0.87	0.06	0.68	0.498	
	age	0.00	0.04	0.00	0.05	0.962	0.01
	BMI	-0.10	0.08	-0.10	-1.21	0.227	
Arch height index（ratio）	gender	0.02	0.01	0.25	3.21	0.002	
	age	0.00	0.00	0.15	1.81	0.072	0.12
	BMI	0.00	0.00	0.23	2.98	0.003	
Arch stiffness index (ratio)	gender	0.01	0.01	0.12	1.47	0.143	
	age	0.00	0.00	0.07	0.85	0.396	0.05
	BMI	0.00	0.00	-0.19	-2.34	0.020	

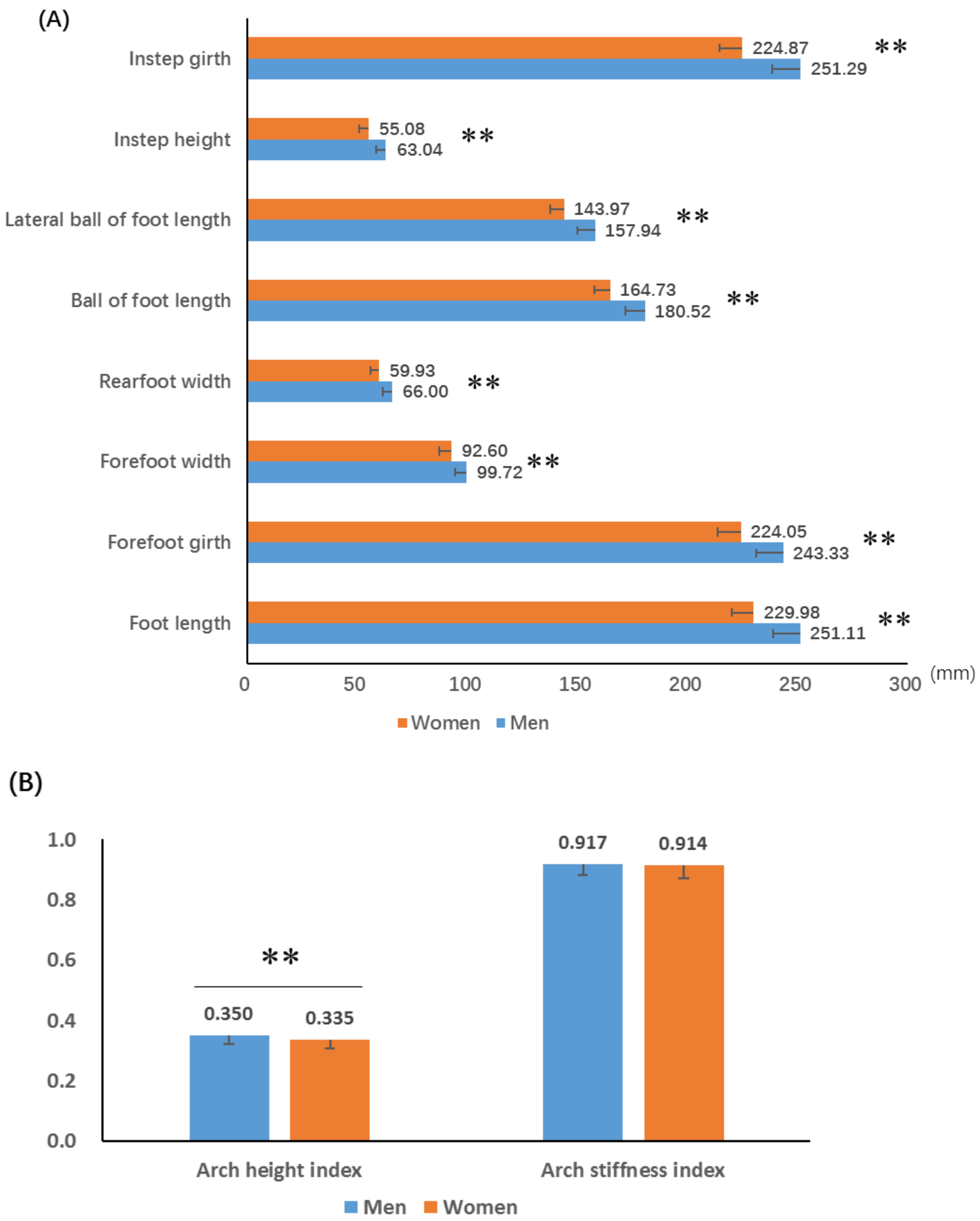


Figure 5-1. Gender differences in foot structure by ANCOVA (adjusted for age and BMI).

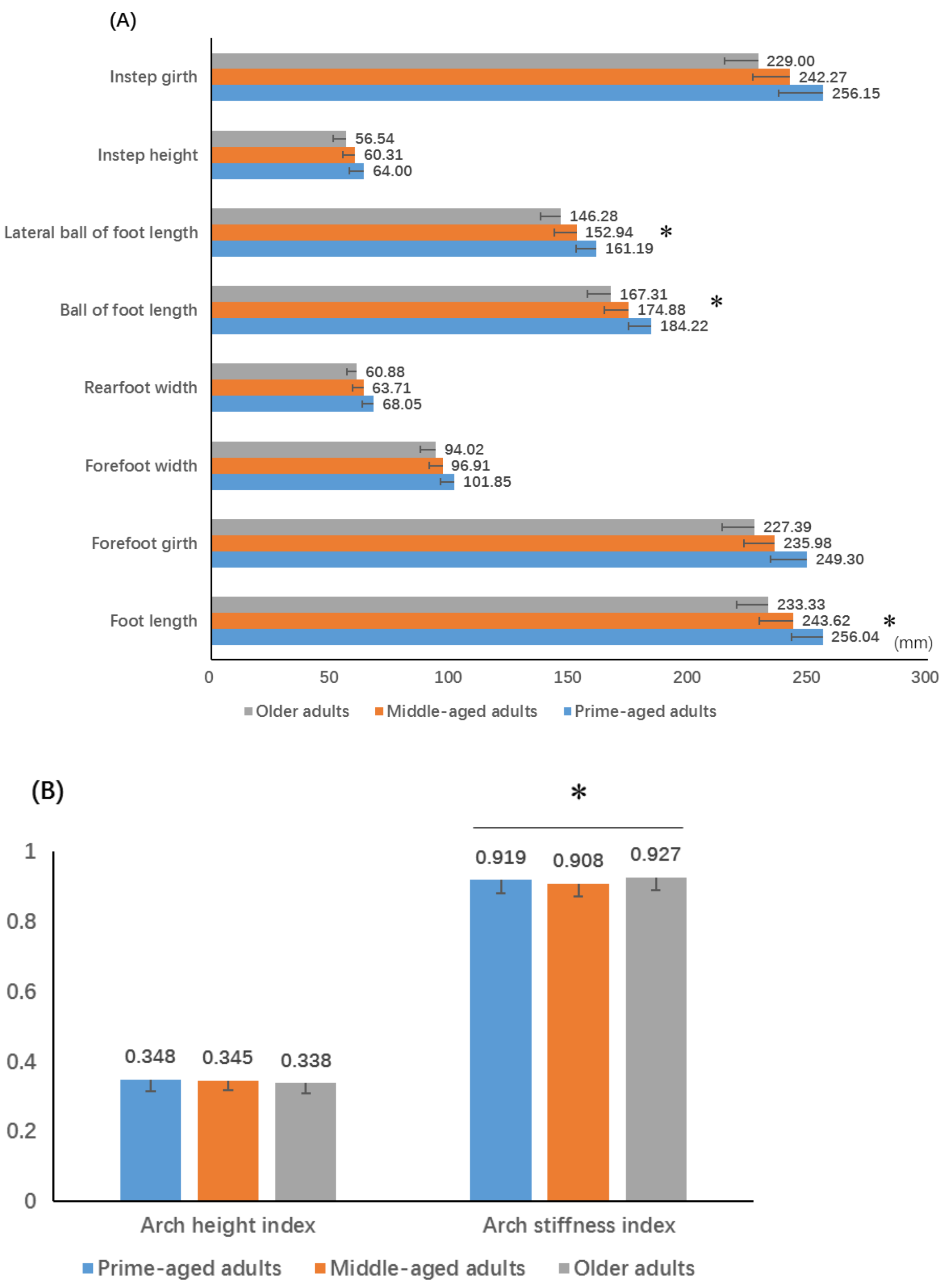


Figure 5-2. Age differences in foot morphology by ANCOVA (adjusted for gender and BMI).

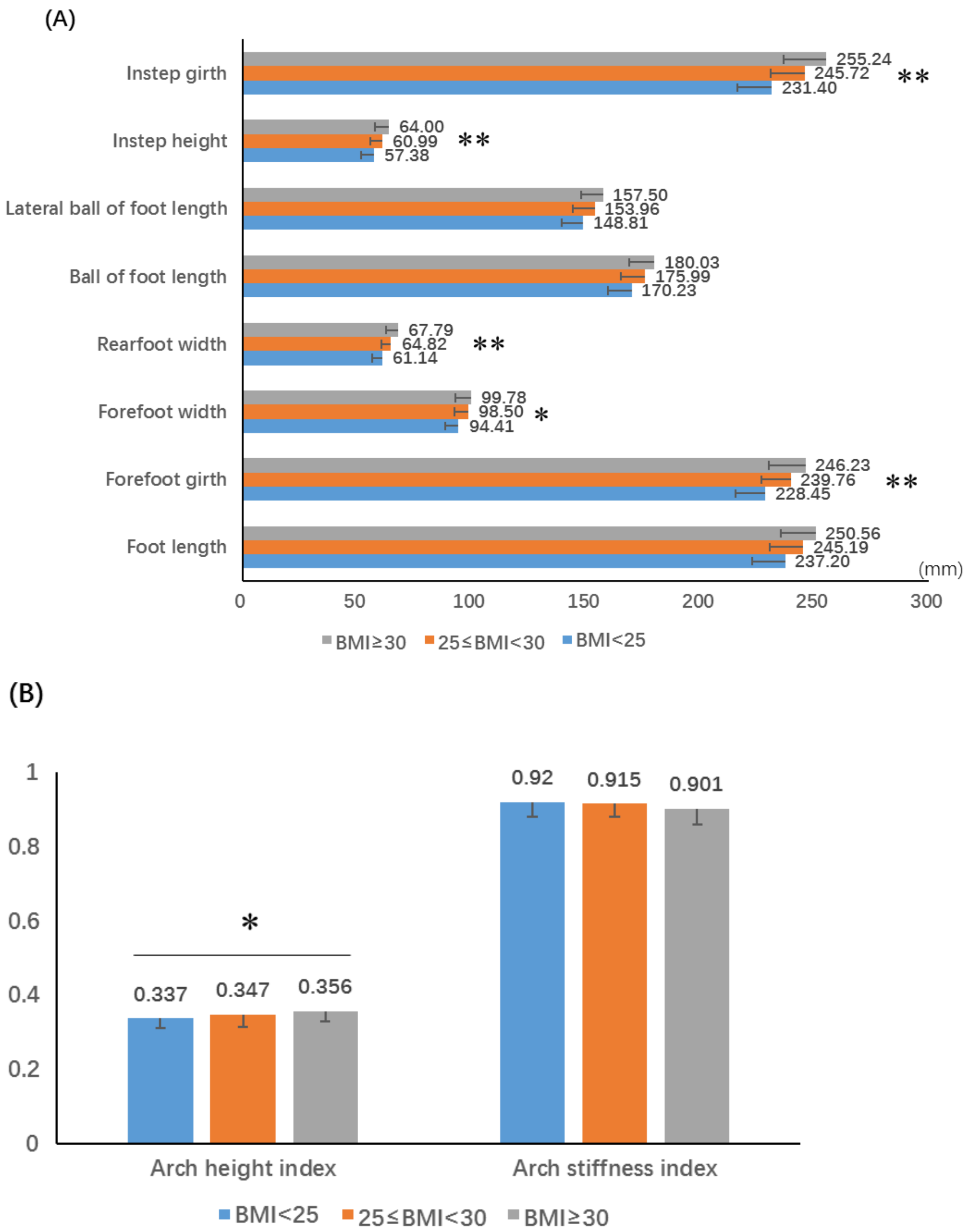


Figure 5-3. BMI differences in foot morphology by ANCOVA (adjusted for age and gender).

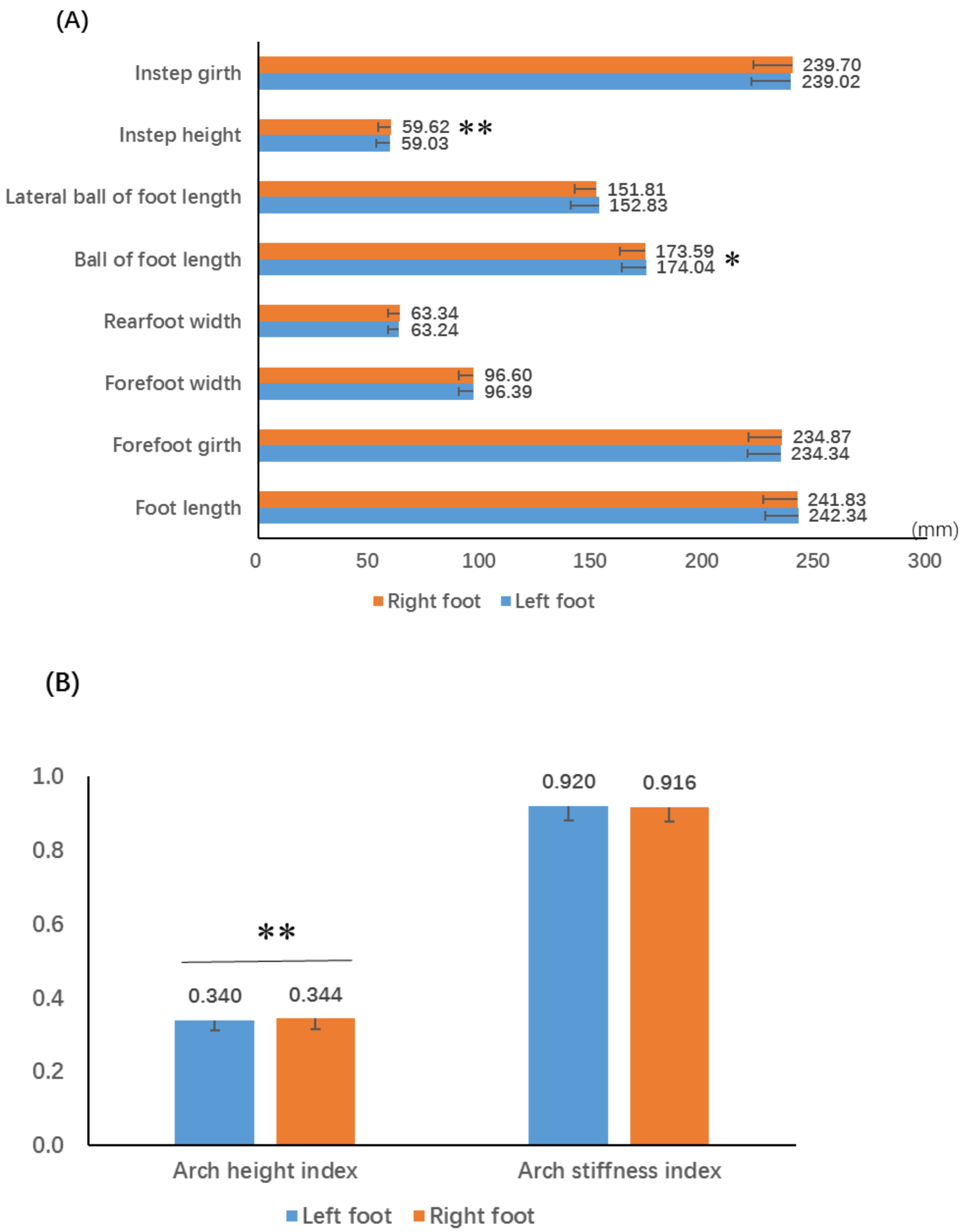


Figure 5-4. Bilateral asymmetry in foot morphology by paired samples t-test.

Chapter 6 (Study 1.2). Association of Obesity with Ankle Muscle Strength

6.1. Introduction

Obesity, as a noted public health concern, is not only linked to chronic medical diseases such as cardiovascular diseases, metabolic syndrome, diabetes, and cancers, but also results in lower extremity musculoskeletal disorders (Kim et al. 2015). It is believed that excess body weight may be a risk factor for the development and progression of foot and ankle disorders. Studies have shown that obese individuals had an increased number of ankle and foot injuries such as sprain (Chaudhry and Egol 2011, Zonfrillo et al. 2008). It has been reported that overweight or obesity was associated with the development and progression of flatfoot, tendinitis, plantar fasciitis, osteoarthritis, and foot pain (Frey and Zamora 2007, Molgaard et al. 2010, Shibuya et al. 2010, Wearing et al. 2006). A probable explanation for the increased foot and ankle disorders in obesity is that the increased body weight may alter the stress distribution within the joint (Astephen and Deluzio 2005, Onwuanyi 2000).

Obesity also changes gait pattern and biomechanical characteristics in lower extremity. Previous studies have demonstrated that obese individuals generally exhibited significantly decreased cadence, walking speed, and step length while increased step width and stance time in order to stabilize and settle the body posture during the gait cycle (McGraw et al. 2000). They also featured as less hip flexion at heel strike throughout a gait cycle (Spyropoulos et al. 1991), and decreased peak knee extensor torque as well as ankle plantar flexor moment when compared with non-obese individuals (DeVita and Hortobágyi 2003). Furthermore, joint motions such as hip adduction, knee adduction, and max stance adduction were greater, and ankle eversion was smaller in obese adults compared with those in non-obese individuals (Lai et al. 2008). The authors attributed the changes of gait pattern and biomechanical characteristics to adaptation to the excess body weight upon the lower extremity.

Studies have repeatedly shown significant differences in foot structure between obese and non-obese individuals. One research investigated fatter and flatter foot structure characteristics via pedograph, and noted that obese children have significantly greater medial midfoot fat pad thickness and lowered medial longitudinal arch height when compared with their leaner counterparts (Riddiford-Harland et al. 2011). A great number of other cross-sectional studies documented that overweight or obese adults are more likely to present with lower medial longitudinal arches than non-obese subjects (Duvigneaud et al. 2008, Shibuya et al. 2010). However, it was known that such fatter and flatter foot may give rise to varying degrees of foot discomfort and pain in both children and adults.

The insufficiency of muscle strength in obese individuals may be responsible for the lower extremity musculoskeletal disorders, the detrimental gait pattern, and the foot structure. To the best of our knowledge, although obesity has been documented to lower muscle strength of knee joint (adjusted for fat-free mass) (Hulens et al. 2001, Kim et al. 2015), to date there has been no evidence related to the association of obesity with ankle muscle strength. With this in mind, the purpose of this study was to compare ankle peak torque and peak torque per body weight which includes plantarflexion, dorsiflexion, eversion and inversion between obese and non-obese adults, and to determine probable association between obesity and a range of ankle muscle strength indicators. Understanding the association between obesity and ankle muscle strength is helpful in the search for preventive or palliative strategy aiming to improve foot and ankle health for podiatrist and patients. It was hypothesized that association existed between obesity and ankle muscle strength.

6.2. Materials and Methods

Participants

Participants were recruited from communities through adverting in local newspapers and distributing study flyers in Tsukuba city and Ise city, Japan in 2015. All the participants volunteered for this study. They had no habit of regular exercise, and had no current or previous foot pain, foot surgery and other neuromuscular or musculoskeletal disorders that affect foot and ankle health. Prior to the study, each participant read and signed informed consent. This study protocol was approved by the Ethics Committee of University of Tsukuba which complied with the Declaration of Helsinki.

Anthropometric and Body Composition

All the anthropometric items have been described in Chapter 4.

Ankle Muscle Strength Measurements

The ankle muscle strength measurements have been described in Chapter 4.

Statistical Analysis

Differences of characteristics of participants between obese and non-obese adults were analyzed using independent samples T test in both men and women. Since muscle strength is related to age (Larsson et al. 1979), an ANCOVA analysis was employed to determine a range of ankle muscle strength differences between obese and non-obese adults adjusted for age. Finally, we utilized partial correlations to examine the association between body fat percentage and ankle muscle strength variables adjusted for age as well. In data analysis, P values less than 0.05 were considered statistically significant. All data analyses were performed with IBM Statistical Package for Social Sciences (SPSS) version 22.0.

6.3. Results

Sixty-nine men and thirty-one women took part in this study. Among them, there were 19 and 12 non-obese, 50 and 19 obese participants in men and women respectively. Description of characteristics of participants is shown in Table 6-1. Except for weight and BMI, independent samples T test did not find significant differences between obese and non-obese groups in age ($P = 0.305$ for men and $P = 0.439$ for women) and height ($P = 0.098$ for men and $P = 0.742$ for women).

Figure 6-1 and Figure 6-2 exhibit ankle muscle strength results between obese and non-obese in men and women after adjusted for age. In both men and women, there was no difference found between obese and non-obese adults in any peak torque. With regard to the peak torque per body weight, however, we observed that obese men had lower values for plantarflexion ($P = 0.062$), dorsiflexion ($P = 0.006$), eversion ($P < 0.001$) and inversion ($P = 0.010$). While in obese women, only lower eversion peak torque per body weight ($P = 0.007$) was found. Although no significant difference appeared, there was still a trend of lower inversion peak torque per body weight ($P = 0.056$).

The correlations between body fat percentage and a range of ankle muscle strength indicators for both men and women adjusted for age are presented in Figure 6-3 and Figure 6-4. It was found that body fat percentage was not correlated with ankle peak torque, but negatively and significantly associated with all the ankle peak torque per body weight in men (r ranged from -0.28 to -0.44, P values < 0.050). With regard to women, there were positive associations between body fat percentage and dorsiflexion peak torque ($r = 0.39$, $P = 0.031$). Besides, it was found that body fat percentage was negatively correlated with eversion ($r = -0.45$, $P = 0.012$) and inversion peak torque per body weight ($r = -0.38$, $P = 0.037$).

6.4. Discussion

The purpose of this study was to investigate probable association between obesity and a range of ankle muscle strength indicators. The main finding was that obesity was negatively associated with eversion and inversion peak torque per body weight in both men and women. The result is supported by previous studies. It has been documented that obesity could more or less lead to alignment of ankle joint such as pronation due to excess body weight (Irving et al. 2007). The malalignment of ankle joint affects forces that cause ligamentous laxity and reduced muscle strength at the joint, which may explain why ankle joint is vulnerable structure and why an increased number of ankle and foot disorders in obese individuals.

In the present study, it was clear that in men, body fat percentage was significantly and negatively correlated with all ankle peak torque per body weight including plantarflexion, dorsiflexion, eversion and inversion respectively. But in women, we only found body fat percentage was negatively associated with eversion and inversion peak torque per body weight. There was a slight gender difference in the relationship between obesity and ankle muscle strength. Similar to our results, the gender difference was also observed in the relationship between body weight and postural performance in a previous study. Menegoni et al (2009) reported that body weight was associated with almost all the considered postural parameters in men, while body weight was only correlated with antero-posterior parameters and center of pressure velocity in women. One possible hypothesis related to the different fat mass distribution could explain this gender difference. In males, fat mass is usually concentrated in the thorax-abdominal region (android fat), while in females, fat mass is generally around the hips and the upper portion of legs (gynoid fat) (Wiklund et al. 2008). The fat mass distribution affects the center of gravity and mass position, which is higher in the android fat than in the gynoid fat. This forces obese men to alter biomechanical characteristics to cope with the higher center of gravity and mass.

There are slightly differences in effect of obesity on lower extremity joints. For instance, in terms of the influence of obesity on knee joint, Tsiros et al (2013) verified the relationship between adiposity and knee joint strength when studying children, and observed that the peak torque was higher and the peak torque per body weight was lower in obesity than healthy non-obese children. A similar result also was reported in adults by Duvigneaud et al (2008). With regard to the influence of obesity on foot and ankle joint, we observed no significant difference between obesity and peak torque, but significantly lowered eversion peak torque per body weight was observed in both obese men and women in our study. It was known that anatomic and biomechanical differences exist between the ankle and knee joint, which may be responsible for the slight difference on the influence of obesity on lower extremity joint.

It is reported that 25% of all sport-related injuries are occurred at foot and ankle (Mack 1982). The incidence of the foot and ankle injuries would enhance theoretically if people gain weight. Zonfrillo et al (2008) evaluated the relationship between overweight and ankle injuries in children, and confirmed that overweight children have an increased risk of ankle injuries than non-obese subjects. Furthermore, Frey and Zamora (2007) compared different BMI group participants with the incidence of foot and ankle disorders when conducting a research of 1411 subjects in an orthopaedic foot and ankle practice. They demonstrated that being overweight or obese significantly increased the chances of having tendinitis, and increased likelihood of plantar fasciitis and osteoarthritis. From our point, the insufficiency of ankle muscle strength may be the cause of increased incidence of foot and ankle injuries and disorders in obese individuals, as previous studies have testified that increased muscle strength is associated with decreased incidence of injuries and osteoarthritis (Hayes and Falconer 1992, Orchard et al. 1997). In our study, lower eversion strength was observed in both obese men and women. In light of these evidences, interventions such as reduced body weight or increased ankle muscle strength should be taken to prevent and improve foot and ankle disorders, thereby promoting the quality of health.

As mentioned in the introduction, overweight or obese individuals always possessed lower walking speed, step length and cadence, and they also had decreased peak knee extensor strength and ankle plantar flexion moment during a gait cycle (DeVita and Hortobágyi 2003, McGraw et al. 2000). Fukagawa et al (1995) investigated the effects of lower extremity strength (knee and ankle extension and flexion), gait and balance on the incidence of falls in nursing home residents utilizing Cybex 340 Isokinetic Dynamometer. Their findings proved that most of the nursing home individuals who had poor balance, gait and occurrence of falls possessed decreased knee and ankle muscle strength. Despite the fact that the gait was not measured in our study, both obese men and women were found to have lower eversion strength. Based on this fact, we consider that the reduced muscle strength in lower extremity probably may result in the corresponding changes of biomechanical characteristics and gait pattern in overweight or obese individuals.

Excess body weight has a negative impact on foot structure and sole arch. Chang et al (2010) indicated that overweight or obese children were 1.39 and 2.66 times more likely to have flatfoot compared non-obese children. With regard to adults, similar results that obese adults had lower medial longitudinal arches were observed (Butterworth et al. 2015, Gill et al. 2014). In our study, we also found that excess body weight has an adverse influence on ankle muscle strength. Muscles around foot and ankle maintain foot structure and support the sole arch, and the insufficiency of muscle strength may give rise to changes of foot structure and sole arch. According to Aydog et al (2005), arch height was impacted by eversion strength in gymnasts. In light of this, decreased body weight and strengthened muscle strength around the foot and ankle joint may be effective methods to maintain foot structure and prevent or improve flatfoot.

6.5. Conclusion

In summary, the results indicate that all ankle peak torque per body weight except plantarflexion was lower in obese men, and body fat percentage was also associated with all ankle peak torque per body weight. While in obese women, we only found eversion peak torque per body weight was lower than non-obese women. Besides, body fat percentage was positively associated with dorsiflexion peak torque, and negatively correlated with eversion and inversion peak torque per body weight. These findings allow for the conclusion that there is an association existed between obesity and ankle muscle strength. A further intervention study is needed to verify whether reduction in body fat and increase in ankle muscle strength are beneficial to foot and ankle health for obese individuals.

Table 6-1. Description of characteristics of participants

	Overweight/obese	Non-obese	P values
Men			
No.	50 (50%)	19 (19%)	-
Age (yrs)	50.46 ± 9.03	52.89 ± 7.87	0.305
Height (cm)	170.27 ± 6.56	173.15 ± 5.84	0.098
Weight (kg)	82.17 ± 10.20	68.51 ± 9.07	< 0.001
BMI (kg/m^2)	28.29 ± 2.62	22.77 ± 2.09	< 0.001
Women			
No.	19 (19%)	12 (12%)	-
Age (yrs)	56.00 ± 10.64	53.33 ± 6.26	0.439
Height (cm)	157.23 ± 5.20	157.93 ± 6.43	0.742
Weight (kg)	75.05 ± 21.65	54.57 ± 7.25	0.004
BMI (kg/m^2)	30.24 ± 7.94	21.83 ± 2.16	0.001

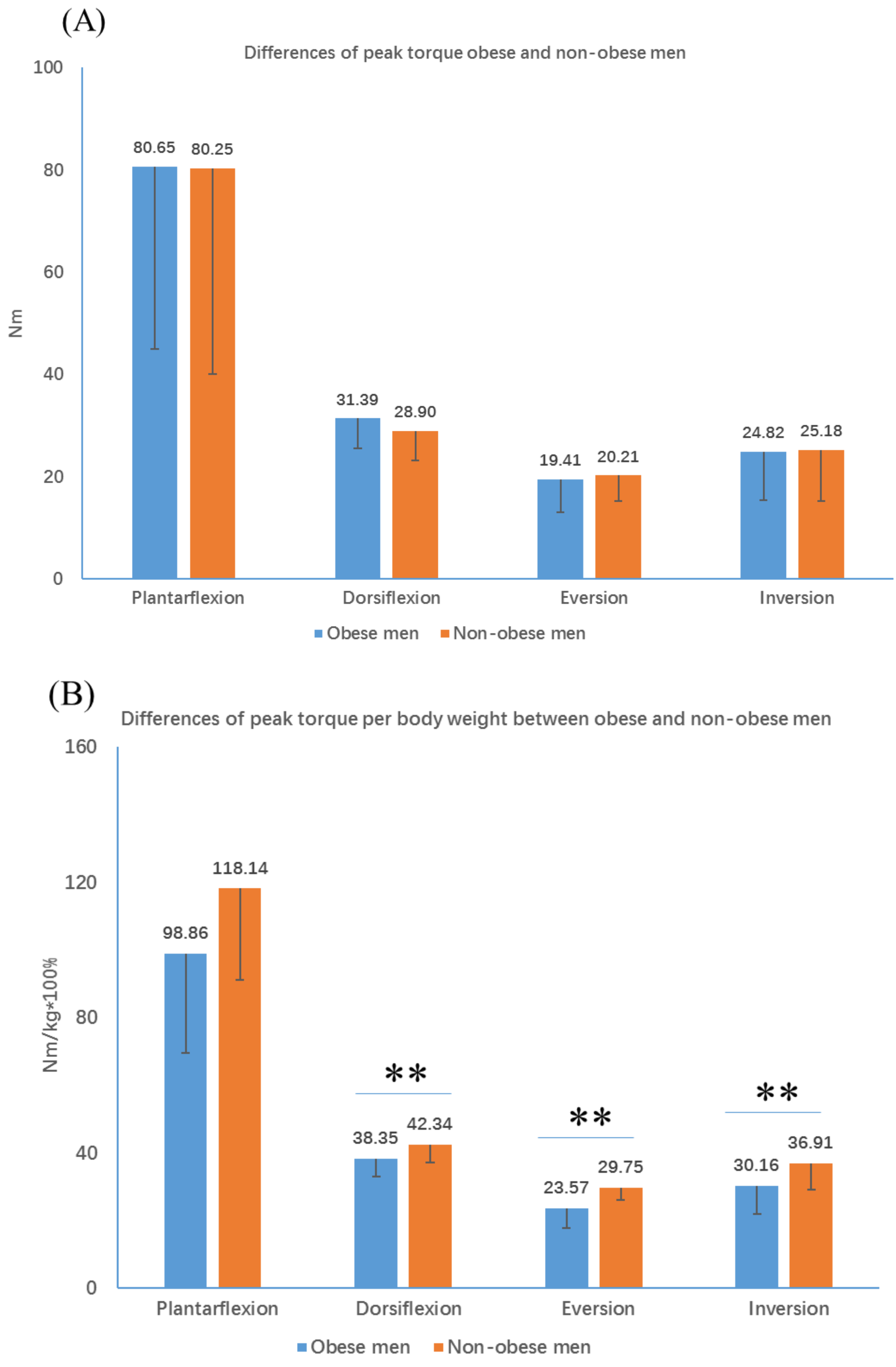
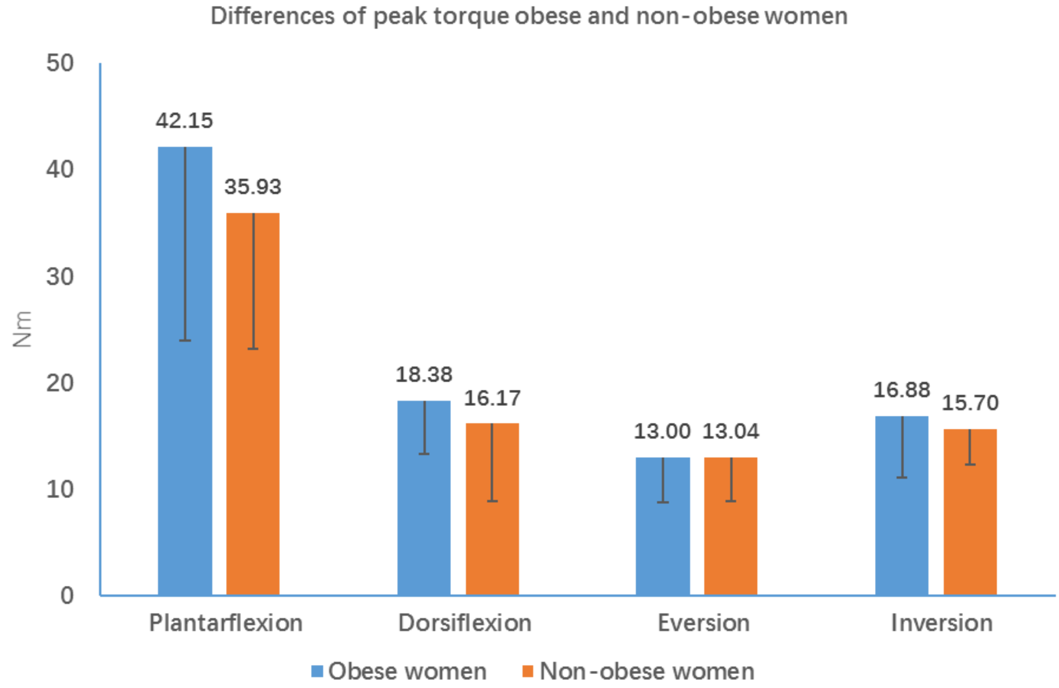


Figure 6-1. Ankle muscle strength differences between obese and non-obese men adjusted for age.

(A)



(B)

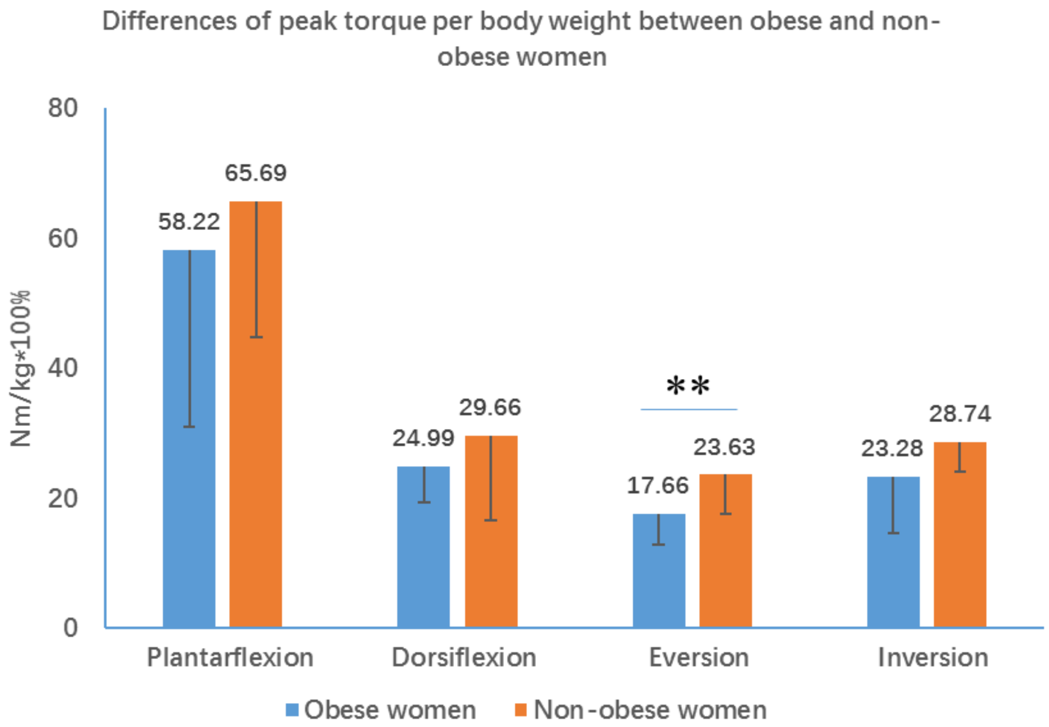
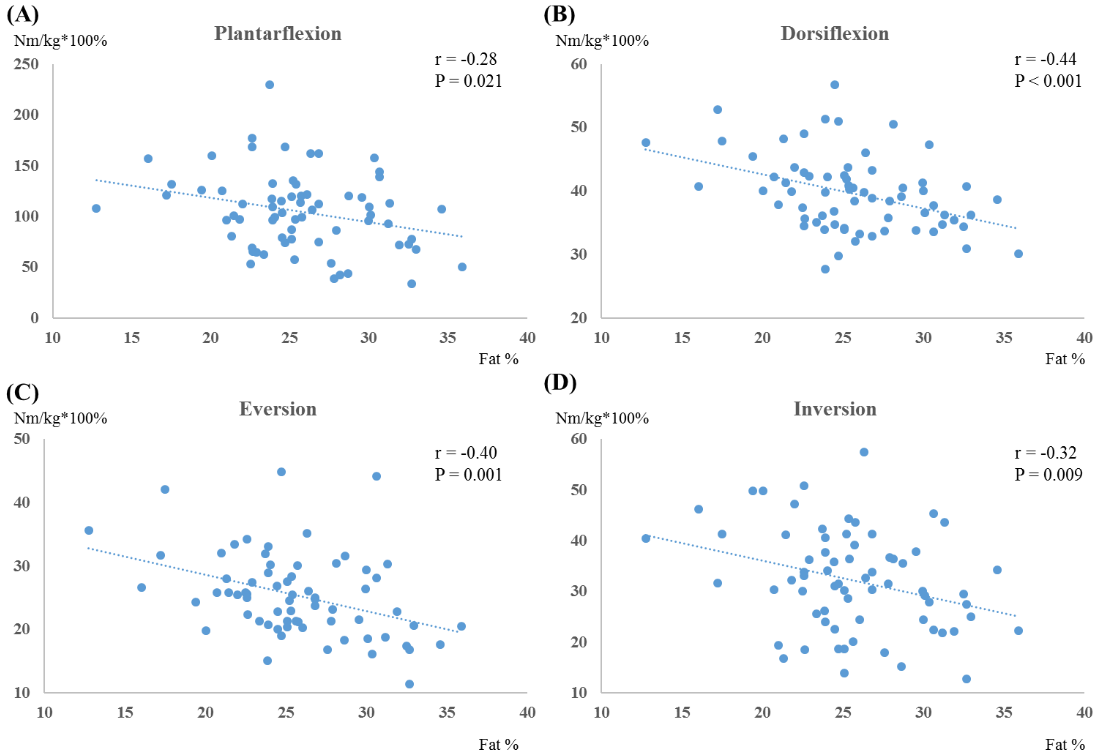


Figure 6-2. Ankle muscle strength differences between obese and non-obese women adjusted for age.



50

Figure 6-3. Correlation between body fat percentage and peak torque per body weight in men adjusted for age.

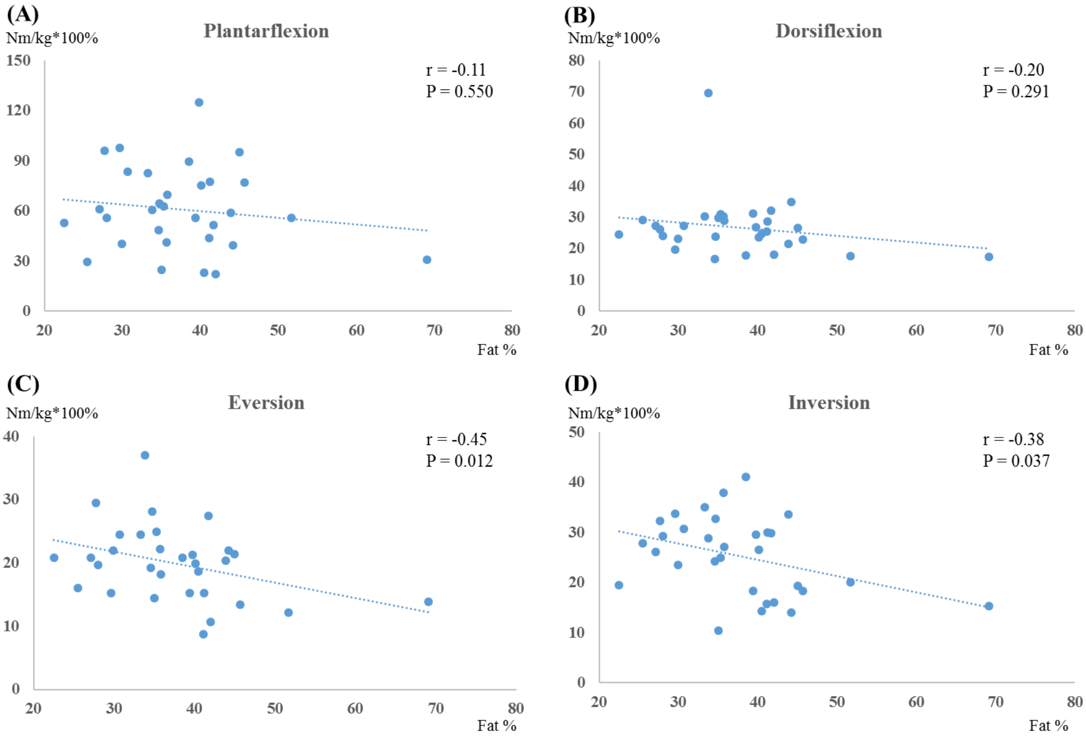


Figure 6-4. Correlation between body fat percentage and peak torque per body weight in women adjusted for age.

Chapter 7 (Study 2.1). Influence of Weight Reduction on Foot Structure and Ankle Muscle Strength

7.1. Introduction

It is known from the latest statistical data published by the World Health Organization that the prevalence of worldwide obesity has more than doubled since 1980, and over 1.9 billion adults were overweight and obese in 2014 (WHO 2015). Obesity is one of major public health concern, and considered to be an epidemic in both developed and developing countries. It has been documented that obesity is not only a major risk factor for internal conditions such as cardiovascular diseases and diabetes (Owen et al. 2015, Shields et al. 2012), but also has a profound impact on lower extremity disorders such as ankle and foot pain (Gay et al. 2014, Irving et al. 2007, Tanamas et al. 2012). For instance, a recent systematic review identifying 25 papers has noted that obesity is strongly related with non-specific foot pain and chronic plantar heel pain in general population (Butterworth et al. 2012). These lower extremity disorders can substantially affect quality of life, and make the obesity more severe.

A possible explanation for the association of obesity with ankle and foot disorders is that excess body weight causes detrimental alterations of foot structure and function (Butterworth et al. 2015). Previous cross-sectional studies have reached a consensus statement that obesity can affect the foot structure. A study measuring dynamic arch index of 81 postmenopausal women exhibited that the excess body weight leads to collapse of the medial longitudinal arch, which adversely affects functional capacity of the foot (Faria et al. 2010). In addition to the arch height, the foot length and width were reported increased significantly with body weight increased when analyzing relationship between anthropometric foot structure and body weight (Morrison et al. 2007). On the other hand, it is known that obesity is characterized by reduced muscle strength. In spite of no direct reports to date, indirect evidences may prove that obesity is associated with lowered ankle muscle strength. It has been shown that obesity has a detrimental impact on balance and ankle instability (Greve et al. 2007, Menegoni et al. 2009), while ankle muscle strength is a strong predictor of the balance and ankle instability (Munn et al. 2003).

Weight reduction is an effective countermeasure to decrease obesity-related health risks and improve quality of life in overweight and obese individuals (Blagojevic et al. 2010, Douketis et al. 2005). However, very few systematic researches have determined how weight reduction affects foot structure and ankle muscle strength. Although a 3-month weight reduction program has been designed to investigate its influence on arch height and plantar peak pressure in obese adults (Song et al. 2015), the previous study did not examine the changes of other foot structure indicators and ankle muscle strength in the program. Furthermore, if weight reduction influence exists in the impact on foot structure and ankle muscle strength, it is necessary to know whether its change rates depend on weight reduction rate.

Therefore, the purpose of this study was to examine the influence of weight reduction induced by a dietary modification on foot structure and ankle muscle strength, and to verify whether its change rates depend on weight reduction rate in obese adults. Conducting such a study is beneficial to better understand the association of weight gain and loss with foot structure and function, and to make clear whether weight reduction is an effective method to improve foot structure and increase ankle muscle strength for obese individuals.

7.2. Materials and Methods

Participants

We recruited participants through advertisements in a local newspaper and distributed flyers from communities near our university. Participants were selected if they met the following eligibility criteria: 1) aged 30 to 65 years old and had a body mass index (BMI) greater than 25 kg/m^2 based on the domestic obesity guideline, 2) had a stable weight for at least three months and no habit of regular exercise, and 3) had no current or previous lower extremity disorders and other neuromuscular or musculoskeletal disorders that affect the foot and ankle health. Initially, a total of 37 obese individuals met these criteria and engaged in our 12-week weight reduction program. One participant was excluded from the analysis due to incomplete data, and three participants were unable to successfully complete the 12-week program because of personal reasons, leaving 33 participants for the final analyses. There were 21 men and 12 women in the participants. Their average age was 53 years, and median BMI was 28.49 kg/m^2 (Table 1). The study was approved by the Ethics Committee of University of Tsukuba which complied with the Helsinki Declaration.

Weight Reduction Program

The weight reduction program has been described in Chapter 4.

Anthropometric Measurements

All the anthropometric measurements have been described in Chapter 4.

Foot Anthropometric Measurements

The foot anthropometric measurements have been described in Chapter 4.

Ankle Muscle Strength Measurements

The ankle muscle strength measurements have been described in Chapter 4.

Statistical Analysis

Considering the independence of assumption of statistical analysis, only the right foot structure and ankle muscle strength data were selected for the main analyses. Because the foot structure and ankle muscle strength indicators were found not to be distributed normally using the Shapiro-Wilks test, the Wilcoxon signed rank test was used to compare differences before and after the weight reduction program. Last, the partial correlations were employed to determine relationship of weight reduction rates with change rates of foot structure, ankle muscle strength after the program, adjusted for age. In data analysis, we considered a P value less than 0.05 to be statistically significant. The data were analyzed with the IBM Statistical Package for Social Sciences (SPSS) version 22.0.

7.3. Results

After the 12-week program, an average of 7.49 kg body weight (9.38%) was reduced (77.82 ± 13.26 versus 70.33 ± 11.37 kg, $P < 0.001$) (Table 7-1). Compared with baseline foot structure characteristics, values of fat foot indicators such as the forefoot girth ($P = 0.012$), rearfoot width ($P = 0.015$) and instep girth ($P = 0.004$) were significantly reduced after the program. While the arch stiffness index was found significantly increased ($P = 0.026$) (Figure 7-1). Regarding ankle muscle strength characteristics after weight reduction, significant decrease was only observed in the dorsiflexion peak torque ($P < 0.001$), but the significant decrease disappeared when considering body weight using peak torque per body weight. With the exception of the dorsiflexion, the rest of the plantarflexion, eversion and inversion peak torque per body weight were found increased significantly ($P < 0.010$) (Figure 7-2).

Table 7-2 shows relationship between change rates of weight reduction and foot structure adjusted for age. The weight reduction rates were significantly associated with the change rates of the instep height ($r = 0.457$, $P = 0.009$) and the instep girth ($r = 0.654$, $P < 0.001$). Although no significant difference was found, there was still a tendency of correlation between the change rates of weight reduction and the forefoot girth ($r = 0.338$, $P = 0.058$). The relationship between change rates of weight reduction and ankle muscle strength is exhibited in Table 7-3. In term of ankle muscle strength, weight reduction rates were related with the plantarflexion and dorsiflexion peak torque ($r = 0.373$, $P = 0.036$; $r = 0.371$, $P = 0.037$, respectively). However, no relationship was exhibited between the change rates of weight reduction and all ankle peak torque per body weight.

7.4. Discussion

The purpose of this study was to determine the influence of weight reduction induced by dietary modification on foot structure and ankle muscle strength. As expected, a 12-week weight reduction program could cause an average of 9.38% weight reduction. Being affected by the weight reduction, we showed that the girth and width of foot become smaller, and the ankle muscle strength increase when comparing to baseline, but no significant change was observed in the arch height index. In addition, the change rates of fat foot indicators such as the instep height, instep girth and arch height index, were found to rely on weight reduction rate significantly, but the change rates of ankle muscle strength adjusted for body weight did not depend on weight reduction rate.

Riddiford-Harland et al (2011) reported that obese children had significantly fatter and flatter feet than those age- and sex-matched non-obese children. Moreover, Wang et al (2004) investigating relationship between body weight and foot parameters of 872 adults reported that BMI was positively related to fat foot indicators such as the height, width and girth of foot. These researches indicate that obese individuals may be more likely to develop a fatter and flatter foot compared to their non-obese counterparts in cross-sectional studies. In our intervention study, we found that fat foot indicators such as the forefoot girth, rearfoot width and instep girth reduced significantly after weight reduction, and the change rates were found to rely on weight reduction rate. However, in spite of a strong association was found between obesity and arch height in cross-sectional studies (Butterworth et al. 2015, Faria et al. 2010), no significant difference was found in the arch height index in our intervention study. One hypothesis to the no difference may be that the arch height is characterized by irreversibility, because its development may be accompanied by a permanent deformation of arch structure due to excess body weight. Therefore, a modest weight reduction during a 12-week program could not cause change of the arch height. In support of our hypothesis, a follow-up survey related to foot structure of pregnant women noted that the decreased arch height caused by pregnancy could not restore even after 19 weeks postpartum (Segal et al. 2013).

Arch stiffness index, defined as the ratio of the standing arch height index divided by the sitting arch height index, is a comprehensive indicator for evaluating foot flexibility. On the basis of the definition of the arch stiffness index, body weight may be an influential factor for the foot flexibility. To illustrate it, Shultz et al (2012) reported that obese individuals always exhibited a more flexible foot when comparing foot structural and functional characteristics in obese and non-obese participants. Consistently, we observed in our study that the foot flexibility decrease significantly after the weight reduction. With these in mind, it is indicated that the body weight has an impact on the foot flexibility.

The present study shows that only the dorsiflexion peak torque decreased significantly, and no significant differences were found in the rest of plantarflexion, eversion and inversion peak torque after weight reduction. However, when adjusted for body weight, except for the dorsiflexion, the rest of the plantarflexion, eversion and inversion peak torque per body weight were found increased significantly. Although absolute muscle strength generally has been considered to decrease with weight reduction induced by dietary modification, performing exercise frequently may result in maintenance of the muscle volume and absolute muscle strength (Weiss et al. 2007). It is known that the muscles, which enable foot to plantarflexion, eversion and inversion rather than dorsiflexion, generally pass the medial and lateral ankle and the planta. Even though no exercise program designed to them, these muscles are still acted to push off and maintain balance as long as human body conducts activities such as walking, which may lead to the absolute muscle strength of plantarflexion, eversion and inversion unchanged while the muscle strength adjusted for body weight increased.

With regard to the lower extremity disorders in response to weight reduction, Henriksen et al (2012) studying the influence of diet-induced weight reduction on osteoarthritis exhibited that the self-reported disability and pain of knee osteoarthritis have been improved significantly. At the same time, the knee muscle strength (normalized to body weight) was increased by 12.0% (extension) and 11.1% (flexion) respectively after a 16-week program. This result indicates that the improvement of lower extremity disorders is generally accompanied by the increase of muscle strength.

In our study, we observed that the plantarflexion, eversion and inversion peak torque per body weight raised by 15.3%, 15.2% and 14.0% respectively during the weight reduction program. From our point of view, the increased ankle muscle strength may improve ankle and foot disorders in obese individuals as well, although ankle and foot disorders had not been investigated in our study.

7.5. Conclusion

In summary, these data indicate that weight reduction induced by a 12-week dietary modification makes the girth and width of foot become smaller, and the ankle muscle strength increase. Besides, the change rates of fat foot indicators depended on weight reduction rate, while the change rates of ankle muscle strength adjusted for body weight did not depend on weight reduction rate. The changes of foot structure and ankle muscle strength after weight reduction may be beneficial for ankle and foot health in obese individuals.

Table 7-1. Anthropometric characteristics before and after weight reduction.

	Before		After		P Value
	Mean	SD	Mean	SD	
Number (female)	33 (12)				
Age (yrs)	53.00	10.18			
Height (cm)	164.75	8.55			
Weight (kg)	77.82	13.26	70.33	11.37	< 0.001
BMI (kg/m^2)	28.49	2.87	25.83	2.58	< 0.001

Table 7-2. Correlation between the change rates of weight reduction and foot structure adjusted for age.

	Δ Foot length	Δ Forefoot girth	Δ Forefoot width	Δ Rearfoot width	Δ Ball of foot length	Δ Lateral ball of foot length
r	-0.262	0.338	0.205	-0.158	-0.246	-0.239
P	0.148	0.058	0.261	0.387	0.175	0.188
	Δ Instep height	Δ Instep girth	Δ First toe angle	Δ Little toe angle	Δ Arch height index	Δ Arch stiffness index
r	0.457	0.654	0.246	-0.183	0.504	-0.150
P	0.009	<0.001	0.174	0.316	0.103	0.411

Table 7-3. Correlation of between the change rates of weight reduction and ankle muscle strength adjusted for age.

Peak torque, Nm	Δ Plantarflexion	Δ Dorsiflexion	Δ Eversion	Δ Inversion
r	0.373	0.371	0.096	0.274
P	0.036	0.037	0.601	0.129
Peak torque per body weight, %	Δ Plantarflexion	Δ Dorsiflexion	Δ Eversion	Δ Inversion
r	0.269	0.052	-0.141	0.085
P	0.136	0.776	0.440	0.643

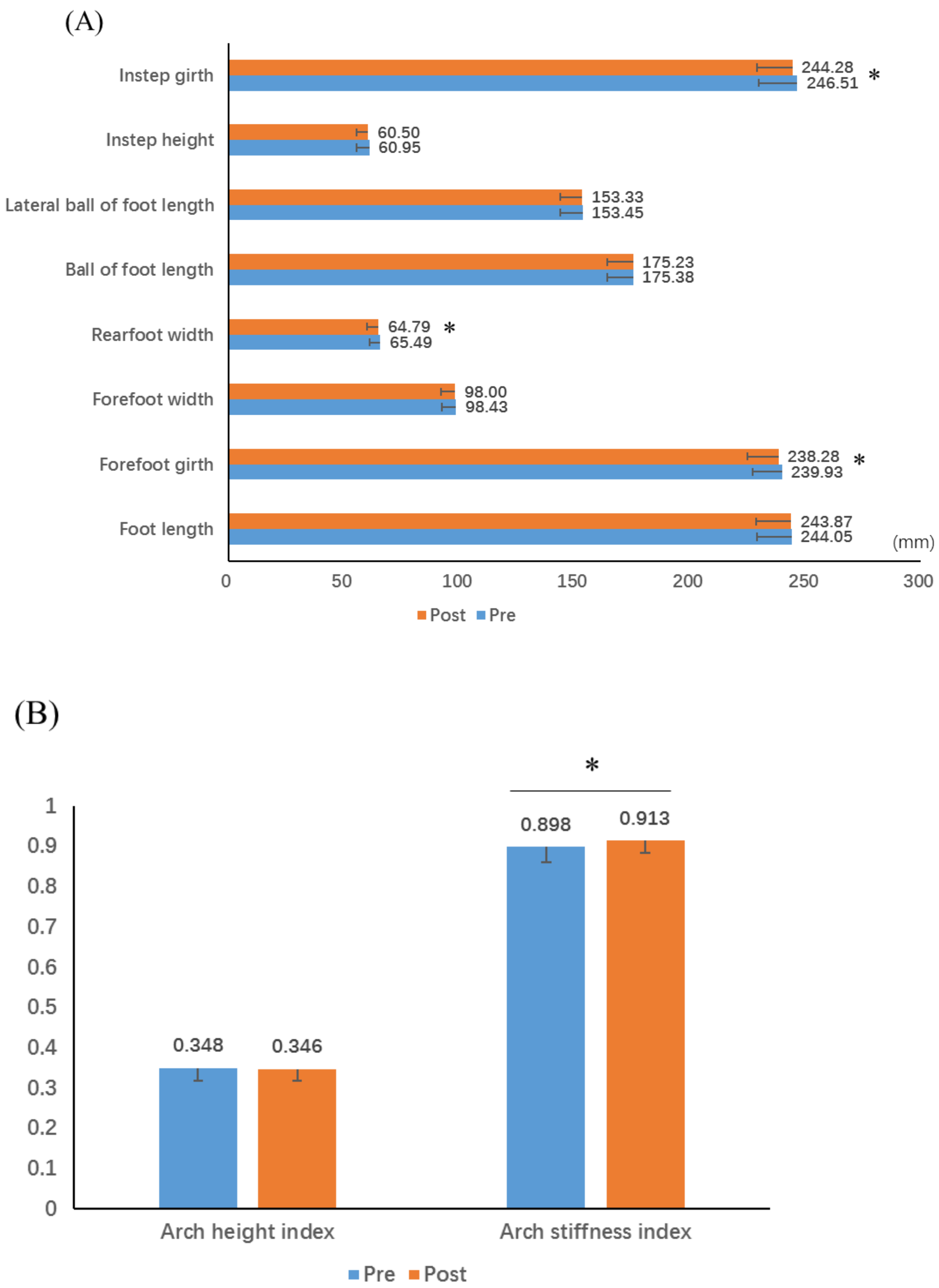


Figure 7-1. Foot structure characteristics before and after weight reduction.

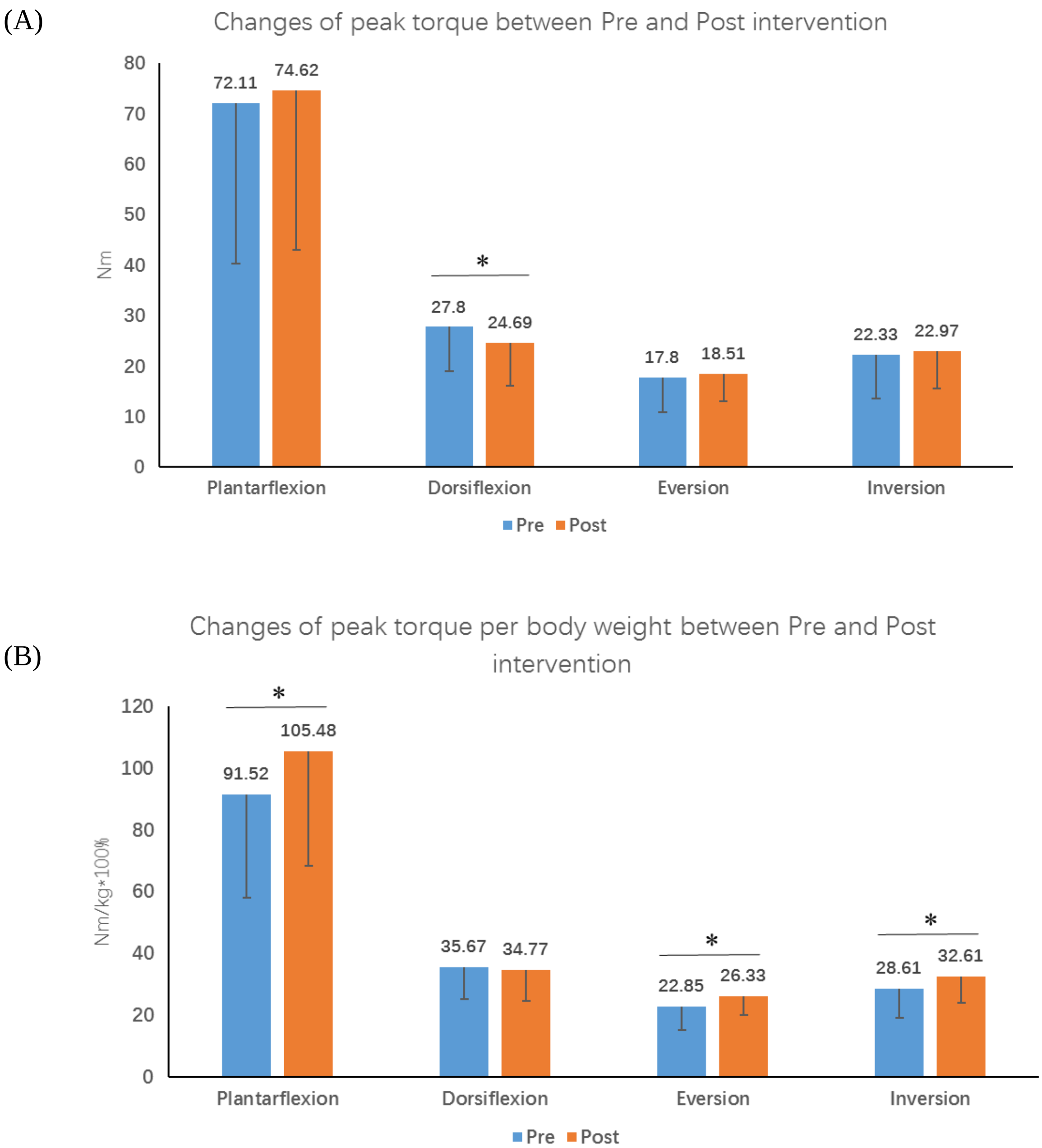


Figure 7-2. Ankle muscle strength characteristics before and after weight reduction.

Chapter 8 (Study 2.2). Influence of Increasing Physical Activity on Foot Structure and Ankle Muscle Strength

8.1. Introduction

The prevalence of obesity has dramatically increased in whether developed or developing countries over the past decades. According to the latest statistical data from the World Health Organization, the worldwide overweight and obese adults had reached more than 1.9 billion in 2014 (WHO 2015). Obesity has become a global pandemic, and recognized as a primary public health concern in many countries. In addition to being a major factor contributing to internal conditions such as cardiovascular diseases and diabetes (Owen et al. 2015, Tanaka et al. 1995), obesity also has a strong relationship with lower extremity disorders such as ankle and foot pain (Frey and Zamora 2007, Ozdemir et al. 2005, Rano et al. 2001), which lowers quality of life (QoL) and makes the obesity become more severe (Macera 2005).

Physical inactivity has been considered as a major contributor to the development and progression of overweight and obesity. A possible explanation for obesity usually accompanied by the physical inactivity is that the excess weight has a negative impact on biomechanical characteristics of lower extremity (Anandacoomarasamy et al. 2008, Wearing et al. 2006). As for the impact on foot and ankle, obesity generally has been reported to be associated with detrimental changes of foot structure and function (Birtane and Tuna 2004, Frey and Zamora 2007, Wearing et al. 2004). For instance, a recent systematic review analyzed 16 papers, reporting that obesity is strongly related with planus (low-arched) foot structure, pronated dynamic foot function and increased plantar pressures when walking (Butterworth et al. 2014). In addition, the physical inactivity also leads to lower level muscle strength in obese individuals. A cross-sectional study has been indicated that obese adults generally had decreased physical activity (PA) and impaired knee strength compared to their non-obese counterparts (Duvigneaud et al. 2008).

Being physically active may be an effective countermeasure to reduce weight, enhance lower extremity function and improve QoL in obese individuals (Rosemann et al. 2008). However, there has been no systematic study on influence of increasing weight bearing PA on foot structure and function in obese adults. Although a 6-month increasing PA intervention was designed to observe its influence on foot structure and plantar peak pressure in obese children (Riddiford-Harland et al. 2016), the study did not investigate the change of ankle muscle strength. Additionally, if changes exist in foot structure and ankle muscle strength during the increasing weight bearing PA, it is necessary to understand whether the foot structure change rate is associated with the ankle muscle strength change rate.

Therefore, the purpose of this study was to examine the influence of increasing weight bearing PA on foot structure and ankle muscle strength in obese adults, and to verify whether the foot structure change rate is related with the ankle muscle strength change rate. Conducting such a study is beneficial to better understand the association of PA with foot structure and function, and to make clear whether the weight bearing PA is an effective approach to improve foot structure and increase ankle muscle strength in obese individuals.

8.2. Materials and Methods

Participants

Participants were recruited through advertisements in a local newspaper and distributed flyers from communities surrounding our university. The participants were selected into our study if they met the following inclusion criteria: age between 30 to 64 years; a body mass index (BMI) greater than 25.0 kg/m^2 based on the domestic obesity guideline (Japan Society for the Study of Obesity 2002); a stable weight for at least 3 months; no habit of regular exercise; and no current or previous lower extremity disorders and other neuromuscular or musculoskeletal disorders that affect the foot and ankle function. Initially, a total of 35 participants met the criteria and entered into our 12-week PA intervention. We excluded 2 participants from the analysis because of incomplete data, and 6 participants who were unable to successfully complete the 12-week intervention due to personal reasons, leaving 27 participants for the final analyses. There were 15 men and 12 women in the participants, with a mean age of 53.07 ± 6.17 years and a mean BMI of 27.42 ± 4.14 kg/m^2 (Table 1). This study was implemented in accordance with the Helsinki Declaration, and the protocol was approved by the Ethics Committee of University of Tsukuba, Japan.

Increasing PA Intervention

The increasing PA intervention has been described in Chapter 4.

Anthropometry and Assessment of PA

All the anthropometric items have been described in Chapter 4.

PA was monitored by an Active Style Pro three-axis accelerometer (HJA-350IT; Omron Healthcare, Kyoto, Japan) which has been validated previously (Ohkawara et al. 2011). The accelerometer was attached to the waist for over 7 consecutive days (including weekend days), except for sleeping or performing water-related activities (e.g., bathing or swimming). We excluded days in which participants wore the accelerometer for less than 10 hours from the data for analysis. The accelerometer counted daily steps and estimated intensity of PA which could be measured over 60-second epochs and recorded as the metabolic equivalent (METs). Based on the intensity, PA was classified as low (1.5-2.9 METs, LPA), moderate (3.0-5.9 METs, MPA) and vigorous intensity (> 6.0 METs, VPA).

Foot Structure Measurement

The foot structure measurement has been described in Chapter 4.

Ankle Muscle Strength Measurement

The ankle muscle strength measurement has been described in Chapter 4.

Statistical Analysis

In consideration of the independence of assumption of statistical analysis, only the right foot structure and ankle muscle strength data were entered into the main analyses. Due to the normal distribution was not observed in foot structure and ankle muscle strength indicators using the Shapiro-Wilks test, we employed the Wilcoxon signed rank test (two related samples test) to compare differences before and after the PA intervention. Then the partial correlations were used to determine the relationship of change rates between the foot structure and the ankle muscle strength after increasing PA, adjusted for age. The data were analyzed with the IBM Statistical Package for Social Sciences (SPSS) version 22.0. A P value less than 0.05 was considered statistically significant.

8.3. Results

Average daily steps increased significantly from 6759 to 10468 ($P < 0.001$). Although no remarkable difference was discovered in LPA, we observed that MPA, VPA or MVPA increased significantly after the 12-week intervention ($P < 0.001$) (Figure 8-1). Under the influence of increasing PA, BMI was observed to decrease significantly (27.42 ± 4.14 versus 26.82 ± 3.89 kg/m^2, $P < 0.001$) (Table 8-1).

Compared with baseline, foot structure indicators such as the foot length ($P = 0.018$), rearfoot width ($P = 0.005$), ball of foot length ($P = 0.038$) and instep girth ($P = 0.019$) reduced remarkably, while the instep height ($P = 0.015$), arch height index ($P = 0.015$) and arch stiffness index ($P = 0.003$) increased significantly (Figure 8-2). However, no significant differences were observed in the forefoot girth and width, first and little toe angle.

With regard to ankle muscle strength after PA intervention (Figure 8-3), we found that only the plantarflexion peak torque increased significantly (P = 0.025), and the dorsiflexion, eversion and inversion peak torque remained stable. While the values of plantarflexion (P = 0.010), dorsiflexion (P = 0.046) and eversion peak torque per body weight (P = 0.019) were found to increase remarkably. However, there was no significant difference in the inversion peak torque per body weight (P = 0.674).

Table 8-2 exhibits correlations of change rates of arch height index and arch stiffness index with change rates of ankle peak torque per body weight, adjusted for age. Although foot structure and ankle muscle strength changed with increasing PA, we found that the change rate of neither the arch height index nor arch stiffness index was significantly associated with the change rates of ankle muscle strength.

8.4. Discussion

The aim of this study was to examine the influence of increased PA on foot structure and ankle muscle strength. The main findings were that the length, width and girth of foot became smaller, and the arch became higher and stiffer; all the ankle peak torque per body weight increased except the inversion after increasing weight bearing PA intervention. Furthermore, although changes were observed in both foot structure and ankle muscle strength, there were no associations of the change rates between foot structure and ankle muscle strength after intervention. It seems that the changes of foot structure and ankle muscle strength associated with increasing PA were independent of each other.

Our results showed that although no significant difference was found in LPA, there was a remarkable increase in MPA, VPA or MVPA during the intervention. Increased PA, especially increased MVPA could not only improve cardiovascular and metabolic health, but also be related with a beneficial effect on functional fitness and performance of daily functioning tasks (Santos et al. 2012). Therefore, increasing weight bearing PA may be one of an effective approach to enhance lower extremity function, thereby improving QoL in obese individuals.

There is a relationship between the presence of a lower arch and increased body weight or BMI (Butterworth et al. 2015, Dunn et al. 2012). It is known that obesity is always accompanied by decreased PA. However, the increasing PA may have a positive impact on arch structure and function in obese individuals. Riddiford-Harland et al (2016) indicated that participating in a PA program leads to increase of the arch height in obese school-aged children, but the increase may be confounded by the growth and development of children. In our study we further proved that only increasing PA could significantly enhance the height of arch. Besides, the arch stiffness, in which the smaller value is associated with soft-tissue injuries of the foot and ankle (Franco 1987), was also found to improve remarkably after PA intervention. Keeping these in mind, we suggest that the structure of arch has a reversible characteristic, and the decrease of PA may be one of major reason for the detrimental changes of arch structure and function in obese individuals.

On the other hand, a cross-sectional study indicated that obese children generally have fatter feet when comparing with those age and sex matched non-obese children

(Riddiford-Harland et al. 2011). Additionally, another study investigated the association of body weight with foot parameters of 872 adults, showing that BMI is related positively to fat foot indicators such as the height, width and girth of foot (Wang et al. 2004). In our study, as anticipated due to increasing PA, the fat foot indicators including the rearfoot width, the instep height and girth were found to reduce significantly in obese adults. Taken together, it is indicated that increasing PA can make the feet become thinner in obese individuals. Therefore, based on all the information from foot structure, increasing weight bearing PA should be recommended to improve arch and foot structure in obese individuals.

It has been widely accepted that obesity is associated with decreased muscle strength (Duvigneaud et al. 2008, Trudelle-Jackson et al. 2011). As for the influence of obesity on ankle muscle strength, in our previous study, we discovered that compared with non-obese individuals, obese adults are more likely to have lowered ankle muscle strength. While the lowered ankle muscle strength is frequently related with declined function of ankle and foot such as instability of the ankle joint (Munn et al. 2003), even ankle sprains (Willems et al. 2002). However, the present study indicated that almost all the ankle muscle strength adjusted for body weight increased after increasing PA intervention. Given the above, we suggest that the increased ankle muscle strength induced by increasing weight bearing PA may improve function of ankle and foot in obese individuals.

As for the change rates in response to the increasing weight bearing PA, neither the change of arch height index nor arch stiffness index had a significant relationship with the change of ankle muscle strength, although foot structure and ankle muscle strength changed with increasing PA. It is indicated that the changes of foot structure and ankle muscle strength associated with increasing weight bearing PA may be independent of each other.

8.5. Conclusion

The results indicate that with increasing weight bearing PA, the length, width and girth of foot become smaller, and the arch become higher and stiffer; the relative ankle muscle strength increases. Besides, both the change of arch height and arch stiffness are not associated with the change of ankle muscle strength. It is suggested that increasing weight bearing PA is one possible approach to improve foot structure and function in obese individuals.

Table 8-1. Anthropometric characteristics before and after a 12-week PA intervention.

	Pre		Post		P value
	Mean	SD	Mean	SD	
Number (female)	27(12)				
Age (yrs)	53.07	6.17			
Height (cm)	166.75	9.89			
Weight (kg)	77.05	14.67	75.35	13.83	< 0.001
BMI (kg/m^2)	27.42	4.14	26.82	3.89	< 0.001

Table 8-2. Correlations of change rates of arch height index and arch stiffness index with change rates of ankle peak torque per body weight adjusted for age.

Δ Arch height index	Δ Plantarflexion	Δ Dorsiflexion	Δ Eversion	Δ Inversion
r	-0.05	0.07	-0.17	-0.09
P	0.794	0.737	0.399	0.675
Δ Arch stiffness index	Δ Plantarflexion	Δ Dorsiflexion	Δ Eversion	Δ Inversion
r	0.02	0.03	-0.06	0.28
P	0.935	0.873	0.755	0.163

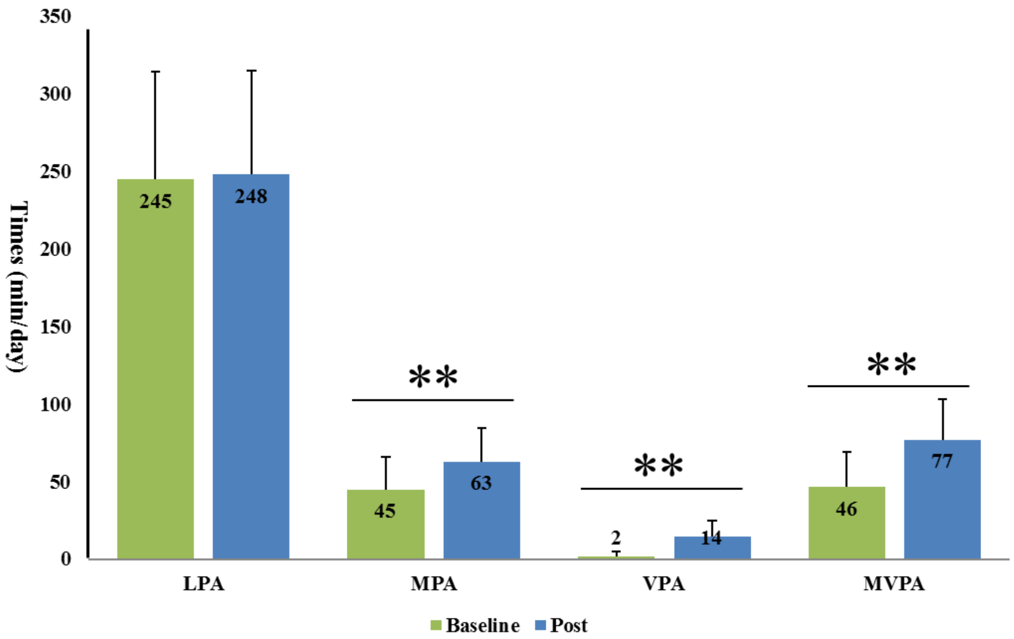


Figure 8-1. The change of PA between baseline and 3 months.
Abbreviations: LPA, low physical activity; MPA, moderate physical activity; VPA, vigorous physical activity; MVPA, moderate and vigorous physical activity.

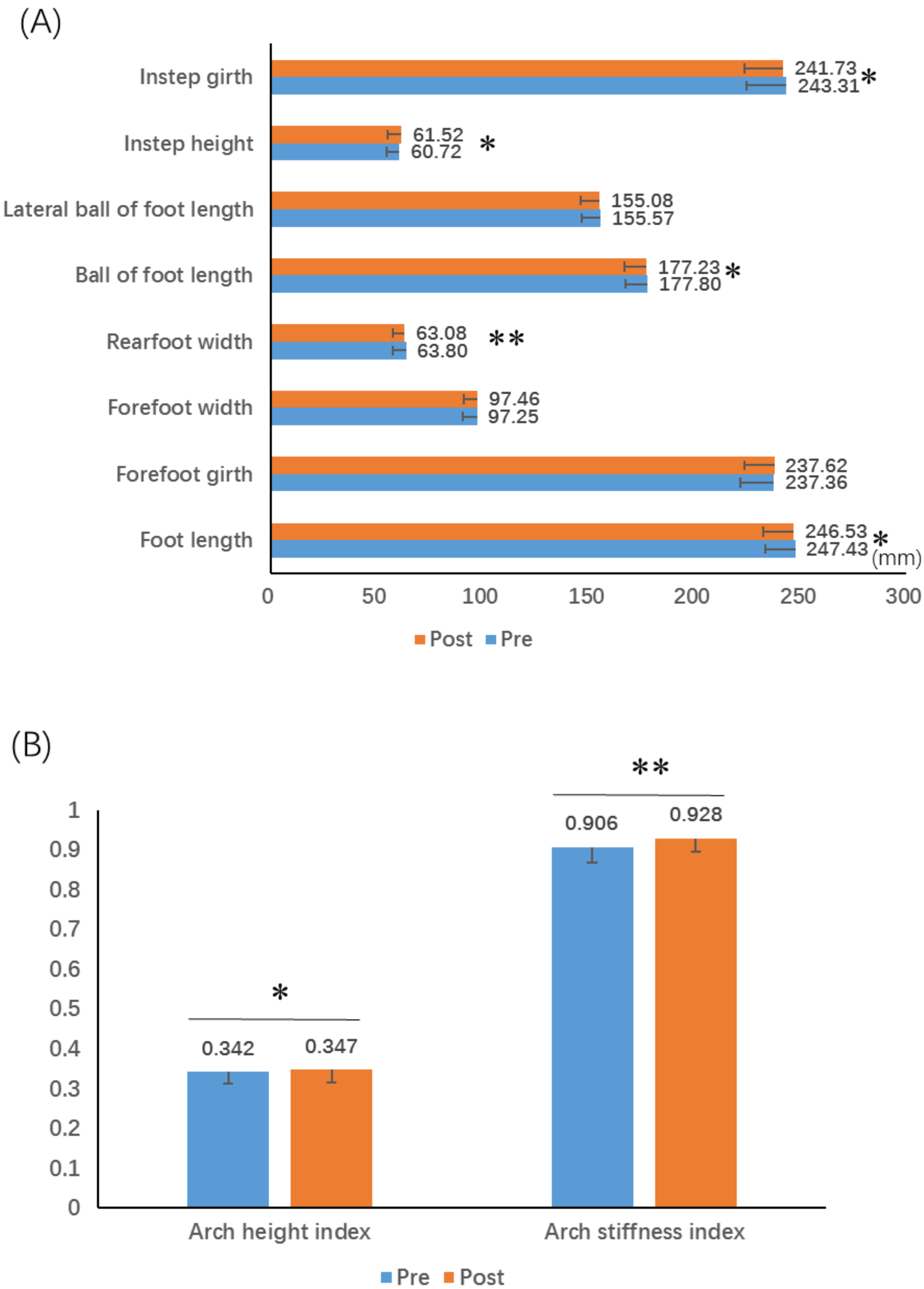
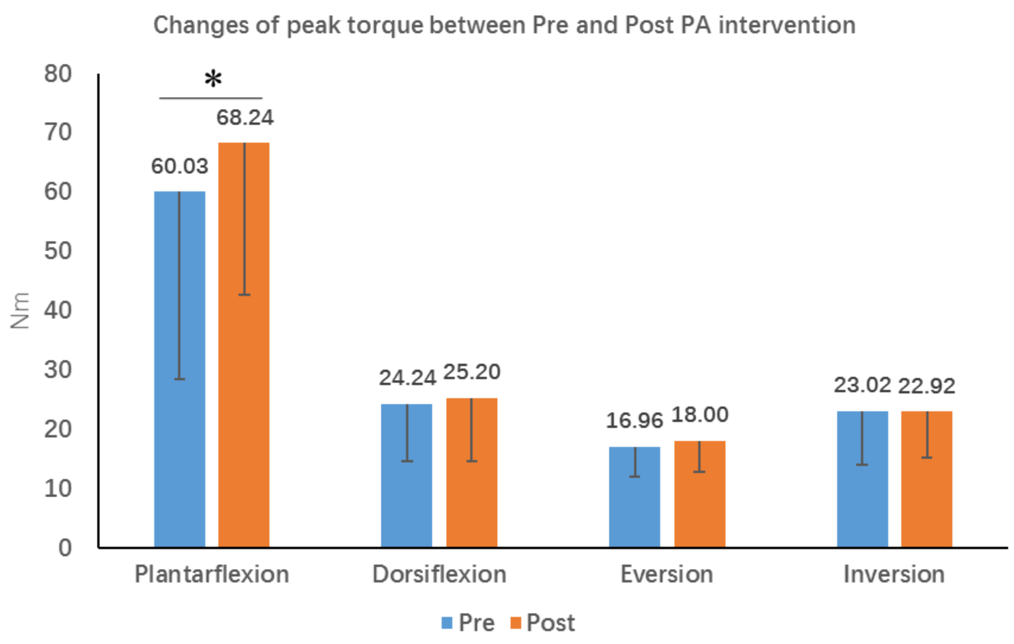


Figure 8-2. Foot structure characteristics before and after a 12-week PA intervention.

(A)



(B)

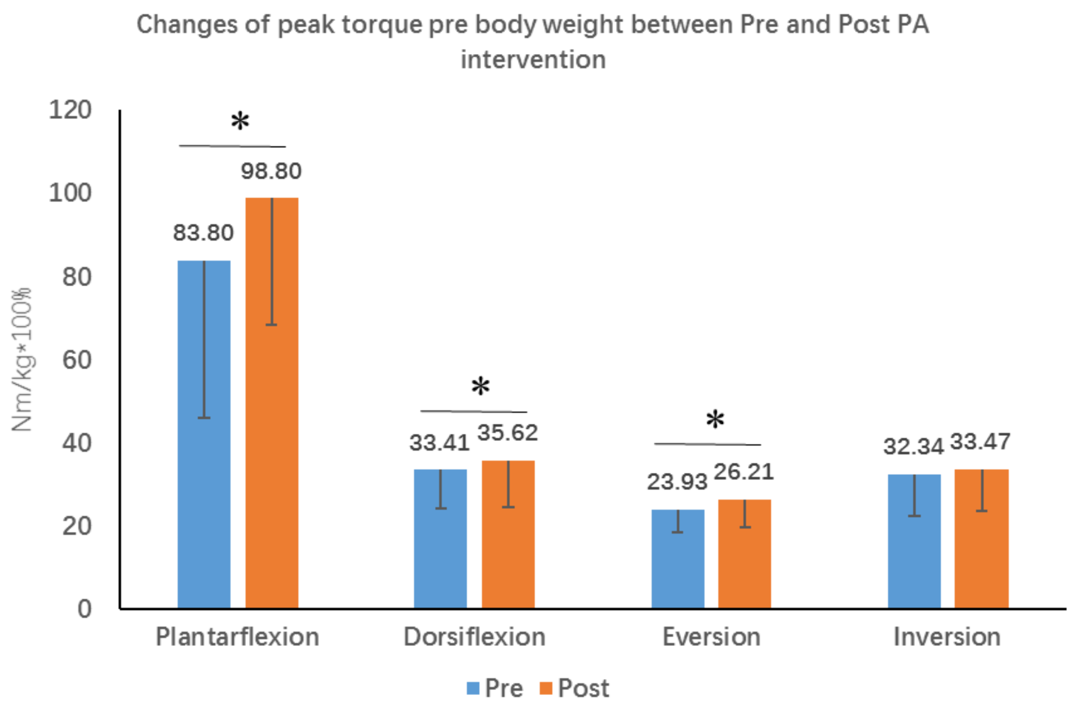


Figure 8-3. Ankle muscle strength characteristics before and after PA intervention.

Chapter 9. General Summary

In these studies, it was investigated that the association of obesity with foot structure and ankle muscle strength, and determined whether weight reduction and increasing weight bearing PA could improve foot structure characteristics and ankle muscle strength. It was found that obesity was associated with width, height and girth of foot, and also had an impact on both AHI and ASI; there was a negative association between obesity and ankle muscle strength; weight reduction induced by dietary modification decreased the girth and width of foot, but not affected arch height. It also made the relative ankle muscle strength increase; increasing weight bearing PA lowered the length, width and girth of foot, and lead to the arch being higher and stiffer. It also enhanced the relative ankle muscle strength.

From the results, it was concluded that due to the influence of excess body weight, obese adults generally had big and fat feet, and decreased ankle muscle strength, which resulted in the change of function of the foot. Furthermore, both weight reduction and increasing weight bearing PA had effect on decreasing fat feet and enhancing ankle muscle strength. However, compared to weight reduction, increasing bearing weight PA may have more beneficial impacts on foot structure and function due to its function of increasing arch height and stiffness.

Chapter 10. Limitations and Future Tasks

In this thesis, it was determined that the influence of weight reduction and increasing weight bearing PA on foot structure and ankle muscle strength.

In study 1, only participants without exercise habit (less than 150 minutes per week) were recruited in the cross-sectional studies to investigate the association of obesity with foot structure and ankle muscle strength. However, exercise habit may affect foot structure and ankle muscle strength. To prove this point, another cross-sectional study should be done to compare the differences between participants with exercise habit and without exercise habit, verifying whether exercise habit has an impact on foot structure and ankle muscle strength in the future.

In study 2, we determined the intervention effect of weight reduction and increasing weight bearing PA on foot structure and ankle muscle strength. It is found that both weight reduction and increasing weight bearing PA have beneficial impact on foot structure and ankle muscle strength. However, it is possible that the intervention of weight reduction combined with increasing weight bearing PA has better effect on foot structure and ankle muscle strength, which needs to be verified in the future studies.

Additionally, in study 2.2, we observed that increasing weight bearing PA, the arches could enhance significantly. In this study, although foot structure characteristics were measured, the pathological bone deformation of flat foot was not investigated. Therefore, it was not clear whether increasing weight bearing PA could improve arch height in those with flat foot.

Besides, gender difference was found to affect foot structure and function in the cross-sectional study, however, it has not been determined deeply in the interventional study due to the small sample sizes. Further studies need to be conducted to examine this aspect.

References

Anandacoomarasamy A, Caterson I, Sambrook P, Fransen M, March L. (2008) **The impact of obesity on the musculoskeletal system**. Int J Obes (Lond). 32(2): 211-222.

Astephen JL, Deluzio KJ. (2005) **Changes in frontal plane dynamics and the loading response phase of the gait cycle are characteristic of severe knee osteoarthritis application of a multidimensional analysis technique**. Clin Biomech (Bristol, Avon). 20(2): 209-217.

Atamturk D. (2009) **Relationship of flatfoot and high arch with main anthropometric variables**. Acta Orthop Traumatol Turc. 43(3): 254-259.

Aurichio TR, Rebelatto JR, De Castro AP. (2011) **The relationship between the body mass index (BMI) and foot posture in elderly people**. Arch Gerontol Geriatr. 52(2): e89-e92.

Aydog ST, Ozcakar L, Tetik O, Demirel HA, Hascelik Z, Doral MN. (2005) **Relation between foot arch index and ankle strength in elite gymnasts: a preliminary study**. Br J Sports Med. 39(3): e13.

Barnes A, Wheat J, Milner C. (2008) **Association between foot type and tibial stress**

injuries: a systematic review. Br J Sports Med. 42(2): 93-98.

Bevans J. (1992) **Biomechanics: a review of foot function in gait**. The Foot. 2(2): 79-82.

Birtane M, Tuna H. (2004) **The evaluation of plantar pressure distribution in obese and non-obese adults**. Clin Biomech (Bristol, Avon). 19(10): 1055-1059.

Blagojevic M, Jinks C, Jeffery A, Jordan KP. (2010) **Risk factors for onset of osteoarthritis of the knee in older adults: a systematic review and meta-analysis**. Osteoarthritis Cartilage. 18(1): 24-33.

Błaszczyk JW, Plewa M, Cieślinska-Swider J, Bacik B, Zahorska-Markiewicz B, Markiewicz A. (2010) **Impact of excess body weight on walking at the preferred speed**. Acta Neurobiol Exp (Wars). 71(4): 528-540.

Brodersen A, Pedersen B, Reimers J. (1993) **Foot deformities and relation to the length of leg muscles in Danish children aged 3-17 years**. Ugeskr Laeger. 155(48): 3914-3916.

Buldt AK, Murley GS, Butterworth P, Levinger P, Menz HB, Landorf KB. (2013) **The relationship between foot posture and lower limb kinematics during walking: A systematic review**. Gait Posture. 38(3): 363-372.

Burns J, Crosbie J, Hunt A, Ouvrier R. (2005) **The effect of pes cavus on foot pain and plantar pressure**. Clin Biomech (Bristol, Avon). 20(9): 877-882.

Burr DB. (1997) **Muscle strength, bone mass, and age-related bone loss**. J Bone Miner Res. 12(10): 1547-1551.

Butterworth PA, Landorf K, Gilleard W, Urquhart D, Menz H. (2014) **The association between body composition and foot structure and function: a systematic review**. Obes Rev. 15(4): 348-357.

Butterworth PA, Landorf KB, Smith S, Menz HB. (2012) **The association between body mass index and musculoskeletal foot disorders: a systematic review**. Obes Rev. 13(7): 630-642.

Butterworth PA, Urquhart DM, Landorf KB, Wluka AE, Cicuttini FM, Menz HB. (2015) **Foot posture, range of motion and plantar pressure characteristics in obese and non-obese individuals**. Gait Posture. 41(2): 465-469.

Cavanagh PR, Morag E, Boulton AJ, Young MJ, Deffner KT, Pammer SE. (1997) **The relationship of static foot structure to dynamic foot function**. J Biomech. 30(3): 243-250.

Chang JH, Wang SH, Kuo CL, Shen HC, Hong YW, Lin LC. (2010) **Prevalence of**

flexible flatfoot in Taiwanese school-aged children in relation to obesity, gender, and age. Eur J Pediatr. 169(4): 447-452.

Chaudhry S, Egol KA. (2011) **Ankle injuries and fractures in the obese patient**. Orthop Clin North Am. 42(1): 45-53.

Chuckpaiwong B, Nunley JA, Mall NA, Queen RM. (2008) **The effect of foot type on in-shoe plantar pressure during walking and running**. Gait Posture. 28(3): 405-411.

Cobb SC, Tis LL, Johnson JT, Wang YT, Geil MD, McCarty FA. (2009) **The effect of low-mobile foot posture on multi-segment medial foot model gait kinematics**. Gait Posture. 30(3): 334-339.

Cowan DN, Jones BH, Robinson JR. (1993) **Foot morphologic characteristics and risk of exercise-related injury**. Arch Fam Med. 2(7): 773-777.

DeVita P, Hortobágyi T. (2003) **Obesity is not associated with increased knee joint torque and power during level walking**. J Biomech. 36(9): 1355-1362.

Donatelli RA. (1985) **Normal biomechanics of the foot and ankle**. J Orthop Sports Phys Ther. 7(3): 91-95.

Douketis JD, Macie C, Thabane L, Williamson DF. (2005) **Systematic review of long-term weight loss studies in obese adults: clinical significance and applicability to clinical practice**. Int J Obes (Lond). 29(10): 1153-1167.

Dowling AM, Steele JR, Baur LA. (2001) **Does obesity influence foot structure and plantar pressure patterns in prepubescent children?** Int J Obes Relat Metab Disord. 25(6): 845-852.

Dunn J, Dunn C, Habbu R, Bohay D, Anderson J. (2012) **Effect of pregnancy and obesity on arch of foot**. Orthop Surg. 4(2): 101-104.

Duvigneaud N, Matton L, Wijndaele K, Deriemaeker P, Lefevre J, Philippaerts R, Thomis M, Delecluse C, Duquet W. (2008) **Relationship of obesity with physical activity, aerobic fitness and muscle strength in Flemish adults**. J Sports Med Phys Fitness. 48(2): 201-210.

Fan Y, Fan Y, Li Z, Lv C, Luo D. (2011) **Natural gaits of the non-pathological flat foot and high-arched foot**. PLoS One. 6(3): e17749.

Faria A, Gabriel R, Abrantes J, Bras R, Moreira H. (2010) **The relationship of body mass index, age and triceps-surae musculotendinous stiffness with the foot arch structure of postmenopausal women**. Clin Biomech (Bristol, Avon). 25(6): 588-593.

Ferber R, Davis IM, Williams DS, 3rd. (2003) **Gender differences in lower extremity mechanics during running**. Clin Biomech (Bristol, Avon). 18(4): 350-357.

Franco AH. (1987) **Pes cavus and pes planus. Analyses and treatment**. Phys Ther. 67(5): 688-694.

Frey C, Zamora J. (2007) **The effects of obesity on orthopaedic foot and ankle pathology**. Foot Ankle Int. 28(9): 996-999.

Fukagawa NK, Wolfson L, Judge J, Whipple R, King M. (1995) **Strength is a major factor in balance, gait, and the occurrence of falls**. J Gerontol A Biol Sci Med Sci. 50(Special Issue): 64-67.

Fukuda I, Kobayashi R. (2008) **The effect of the toes-grip training in healthy young adults**. Phys Ther Jpn. 35: 261-266.

Funk DA, Cass JR, Johnson KA. (1986) **Acquired adult flat foot secondary to posterior tibial-tendon pathology**. J Bone Joint Surg Am. 68(1): 95-102.

Güven G, Özden H, Akalın A, Çolak E. (2009) **Comparative evaluation of the foot measurements of women who presented to the obesity outpatient clinic in Eskişehir Osmangazi University**. Türkiye Klinikleri Tıp Bilimleri Dergisi.

29(5): 1253-1259.

Gay A, Culliford D, Leyland K, Arden NK, Bowen CJ. (2014) **Associations between body mass index and foot joint pain in middle-aged and older women: a longitudinal population-based cohort study**. Arthritis Care Res (Hoboken). 66(12): 1873-1879.

Gill SV, Lewis CL, DeSilva JM. (2014) **Arch height mediation of obesity-related walking in adults: contributors to physical activity limitations**. Physiol J. 2014.

Gray H. (1918) **Anatomy of the human body**. Lea & Febiger.

Greve J, Alonso A, Bordini ACP, Camanho GL. (2007) **Correlation between body mass index and postural balance**. Clinics. 62(6): 717-720.

Hamill J, Bates B, Knutzen K, Kirkpatrick G. (1989) **Relationship between selected static an dynamic lower extremity measures**. Clin Biomech (Bristol, Avon). 4(4): 217-225.

Hashimoto T, Sakuraba K. (2014) **Strength training for the intrinsic flexor muscles of the foot: effects on muscle strength, the foot arch, and dynamic parameters before and after the training**. J Phys Ther Sci. 26(3): 373-376.

Hayes KW, Falconer J. (1992) **Differential muscle strength decline in osteoarthritis of the knee. A developing hypothesis**. Arthritis Care Res. 5(1): 24-28.

Henriksen M, Christensen R, Danneskiold-Samsoe B, Bliddal H. (2012) **Changes in lower extremity muscle mass and muscle strength after weight loss in obese patients with knee osteoarthritis: a prospective cohort study**. Arthritis Rheum. 64(2): 438-442.

Hintermann B, Nigg B, Sommer C, Cole G. (1994) **Transfer of movement between calcaneus and tibia in vitro**. Clin Biomech (Bristol, Avon). 9(6): 349-355.

Horton MG, Hall TL. (1989) **Quadriceps femoris muscle angle: normal values and relationships with gender and selected skeletal measures**. Phys Ther. 69(11): 897-901.

Hulens M, Vansant G, Lysens R, Claessens AL, Muls E, Brumagne S. (2001) **Study of differences in peripheral muscle strength of lean versus obese women: an allometric approach**. Int J Obes Relat Metab Disord. 25(5): 676-681.

Hunt AE, Smith RM. (2004) **Mechanics and control of the flat versus normal foot during the stance phase of walking**. Clin Biomech (Bristol, Avon). 19(4): 391-397.

Irving DB, Cook JL, Young MA, Menz HB. (2007) **Obesity and pronated foot type may increase the risk of chronic plantar heel pain: a matched case-control study**. BMC Musculoskelet Disord. 8: 41.

Japan Society for the Study of Obesity. (2002) **New criteria for 'obesity disease' in Japan**. Circ J. 66(11): 987-992.

Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. (1999) **The effect of foot structure and range of motion on musculoskeletal overuse injuries**. Am J Sports Med. 27(5): 585-593.

Kaye RA, Jahss MH. (1991) **Tibialis posterior: a review of anatomy and biomechanics in relation to support of the medial longitudinal arch**. Foot Ankle. 11(4): 244-247.

Keles P, Diyarbakirli S, Tan M, Tan U. (1997) **Facial asymmetry in right- and left-handed men and women**. Int J Neurosci. 91(3-4): 147-159.

Kelly LA, Cresswell AG, Racinais S, Whiteley R, Lichtwark G. (2014) **Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch**. J R Soc Interface. 11(93): 20131188.

Kernozek TW, Ricard MD. (1990) **Foot placement angle and arch type: effect on**

rearfoot motion. Arch Phys Med Rehabil. 71(12): 988-991.

Kernozek TW, Torry MR, Van Hoof H, Cowley H, Tanner S. (2005) **Gender differences in frontal and sagittal plane biomechanics during drop landings**. Med Sci Sports Exerc. 37(6): 1003-1012.

Kim B, Tsujimoto T, So R, Tanaka K. (2015) **Changes in lower extremity muscle mass and muscle strength after weight loss in obese men: A prospective study**. Obes Res Clin Pract. 9(4): 365-373.

Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M. (1994) **Clinical rating systems for the ankle-hindfoot, midfoot, hallux, and lesser toes**. Foot Ankle Int. 15(7): 349-353.

Kulig K, Burnfield JM, Reischl S, Requejo SM, Blanco CE, Thordarson DB. (2005) **Effect of foot orthoses on tibialis posterior activation in persons with pes planus**. Med Sci Sports Exerc. 37(1): 24-29.

Kura H, Luo ZP, Kitaoka HB, An KN. (1997) **Quantitative analysis of the intrinsic muscles of the foot**. Anat Rec. 249(1): 143-151.

Lai PP, Leung AK, Li AN, Zhang M. (2008) **Three-dimensional gait analysis of obese adults**. Clin Biomech (Bristol, Avon). 23 Suppl 1: S2-6.

Larsson L, Grimby G, Karlsson J. (1979) **Muscle strength and speed of movement in relation to age and muscle morphology**. J Appl Physiol Respir Environ Exerc Physiol. 46(3): 451-456.

Lee YC, Lin G, Wang MJ. (2014) **Comparing 3D foot scanning with conventional measurement methods**. J Foot Ankle Res. 7(1): 44.

Lehnert T, Sonntag D, Konnopka A, Riedel-Heller S, Konig HH. (2013) **Economic costs of overweight and obesity**. Best Pract Res Clin Endocrinol Metab. 27(2): 105-115.

Lhoste-Trouilloud A. (2012) **The tibialis posterior tendon**. J Ultrasound. 15(1): 2-6.

Macera CA. (2005) **Obesity, physical activity, and the risk of decline in health and mobility**. Clin J Sport Med. 15(3): 200-201.

Mack RP. (1982) **Ankle injuries in athletics**. Clin Sports Med. 1(1): 71-84.

Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. (2001) **A comparison of knee joint motion patterns between men and women in selected athletic tasks**. Clin Biomech (Bristol, Avon). 16(5): 438-445.

Mann R, Inman VT. (1964) **Phasic activity of intrinsic muscles of the foot**. J Bone

Joint Surg Am. 46: 469-481.

Markolf KL, Mensch JS, Amstutz HC. (1976) **Stiffness and laxity of the knee--the contributions of the supporting structures. A quantitative in vitro study**. J Bone Joint Surg Am. 58(5): 583-594.

Mathieson I, Upton D, Prior TD. (2004) **Examining the validity of selected measures of foot type: a preliminary study**. J Am Podiatr Med Assoc. 94(3): 275-281.

Matsuo T, Kato Y, Murotake Y, Kim MK, Unno H, Tanaka K. (2010) **An increase in high-density lipoprotein cholesterol after weight loss intervention is associated with long-term maintenance of reduced visceral abdominal fat**. Int J Obes (Lond). 34(12): 1742-1751.

Mauch M, Grau S, Krauss I, Maiwald C, Horstmann T. (2008) **Foot morphology of normal, underweight and overweight children**. Int J Obes (Lond). 32(7): 1068-1075.

McCarthy DJ, Sperandio CP. (1993) **Anatomical basis for congenital deformities of the lower extremities. Part III. The foot and ankle**. J Am Podiatr Med Assoc. 83(4): 203-214.

McGraw B, McClenaghan BA, Williams HG, Dickerson J, Ward DS. (2000) **Gait and postural stability in obese and nonobese prepubertal boys**. Arch Phys Med Rehabil. 81(4): 484-489.

Mei-Dan O, Kahn G, Zeev A, Rubin A, Constantini N, Even A, Nyska M, Mann G. (2005) **The medial longitudinal arch as a possible risk factor for ankle sprains: a prospective study in 83 female infantry recruits**. Foot Ankle Int. 26(2): 180-183.

Menegoni F, Galli M, Tacchini E, Vismara L, Cavigioli M, Capodaglio P. (2009) **Gender-specific effect of obesity on balance**. Obesity (Silver Spring). 17(10): 1951-1956.

Menz HB. (2004) **Two feet, or one person? Problems associated with statistical analysis of paired data in foot and ankle medicine**. The Foot. 14(1): 2-5.

Menz HB, Morris ME, Lord SR. (2005) **Foot and ankle characteristics associated with impaired balance and functional ability in older people**. J Gerontol A Biol Sci Med Sci. 60(12): 1546-1552.

Messier SP, Davies AB, Moore DT, Davis SE, Pack RJ, Kazmar SC. (1994) **Severe obesity: effects on foot mechanics during walking**. Foot Ankle Int. 15(1): 29-34.

Miller EE, Whitcome KK, Lieberman DE, Norton HL, Dyer RE. (2014) **The effect of minimal shoes on arch structure and intrinsic foot muscle strength**. J Sport Health Sci. 3(2): 74-85.

Molgaard C, Lundbye-Christensen S, Simonsen O. (2010) **High prevalence of foot problems in the Danish population: a survey of causes and associations**. Foot (Edinb). 20(1): 7-11.

Morrison SC, Durward BR, Watt GF, Donaldson MD. (2007) **Anthropometric foot structure of peripubescent children with excessive versus normal body mass: a cross-sectional study**. J Am Podiatr Med Assoc. 97(5): 366-370.

Mulligan EP, Cook PG. (2013) **Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function**. Man Ther. 18(5): 425-430.

Munn J, Beard DJ, Refshauge KM, Lee RY. (2003) **Eccentric muscle strength in functional ankle instability**. Med Sci Sports Exerc. 35(2): 245-250.

Nawoczenski DA, Saltzman CL, Cook TM. (1998) **The effect of foot structure on the three-dimensional kinematic coupling behavior of the leg and rear foot**. Phys Ther. 78(4): 404-416.

Nigg BM, Cole GK, Nachbauer W. (1993) **Effects of arch height of the foot on angular motion of the lower extremities in running**. J Biomech. 26(8): 909-916.

Nix S, Smith M, Vicenzino B. (2010) **Prevalence of hallux valgus in the general population: a systematic review and meta-analysis**. J Foot Ankle Res. 3: 21.

Ohkawara K, Oshima Y, Hikihara Y, Ishikawa-Takata K, Tabata I, Tanaka S. (2011) **Real-time estimation of daily physical activity intensity by a triaxial accelerometer and a gravity-removal classification algorithm**. Br J Nutr. 105(11): 1681-1691.

Onwuanyi O. (2000) **Calcaneal spurs and plantar heel pad pain**. The Foot. 10(4): 182-185.

Orchard J, Marsden J, Lord S, Garlick D. (1997) **Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers**. Am J Sports Med. 25(1): 81-85.

Owen CG, Kapetanakis VV, Rudnicka AR, Wathern AK, Lennon L, Papacosta O, Cook DG, Wannamethee SG, Whincup PH. (2015) **Body mass index in early and middle adult life: prospective associations with myocardial infarction, stroke and diabetes over a 30-year period: the British Regional Heart Study**.

BMJ Open. 5(9): e008105.

Ozdemir H, Yilmaz E, Murat A, Karakurt L, Poyraz AK, Ogur E. (2005) **Sonographic evaluation of plantar fasciitis and relation to body mass index**. Eur J Radiol. 54(3): 443-447.

Paiva de Castro A, Rebelatto JR, Aurichio TR. (2011) **The effect of gender on foot anthropometrics in older people**. J Sport Rehabil. 20(3): 277-286.

Patil V, Ebraheim NA, Frogameni A, Liu J. (2007) **Morphometric dimensions of the calcaneonavicular (spring) ligament**. Foot Ankle Int. 28(8): 927-932.

Plato CC, Wood JL, Norris AH. (1980) **Bilateral asymmetry in bone measurements of the hand and lateral hand dominance**. Am J Phys Anthropol. 52(1): 27-31.

Pohl MB, Buckley JG. (2008) **Changes in foot and shank coupling due to alterations in foot strike pattern during running**. Clin Biomech (Bristol, Avon). 23(3): 334-341.

Powell DW, Long B, Milner CE, Zhang S. (2011) **Frontal plane multi-segment foot kinematics in high- and low-arched females during dynamic loading tasks**. Hum Mov Sci. 30(1): 105-114.

Prince F, Corriveau H, Hébert R, Winter DA. (1997) **Gait in the elderly**. Gait Posture. 5(2): 128-135.

Purves D, White LE, Andrews TJ. (1994) **Manual asymmetry and handedness**. Proc Natl Acad Sci USA. 91(11): 5030-5032.

Rano JA, Fallat LM, Savoy-Moore RT. (2001) **Correlation of heel pain with body mass index and other characteristics of heel pain**. J Foot Ankle Surg. 40(6): 351-356.

Rathleff MS, Richter C, Brushoj C, Bencke J, Bandholm T, Holmich P, Thorborg K. (2014) **Increased medial foot loading during drop jump in subjects with patellofemoral pain**. Knee Surg Sports Traumatol Arthrosc. 22(10): 2301-2307.

Razeghi M, Batt ME. (2002) **Foot type classification: a critical review of current methods**. Gait Posture. 15(3): 282-291.

Rein S, Fabian T, Zwipp H, Mittag-Bonsch M, Weindel S. (2010) **Influence of age, body mass index and leg dominance on functional ankle stability**. Foot Ankle Int. 31(5): 423-432.

Richards C, Card K, Song J, Hillstrom H, Butler R, Davis I. (2003) **A novel arch height index measurement system (AHIMS): intra-and inter-rater**

reliability. Proceedings of American Society of Biomechanics Annual Meeting Toledo.

Riddiford-Harland DL, Steele JR, Baur LA. (2011) **Are the feet of obese children fat or flat? Revisiting the debate**. Int J Obes (Lond). 35(1): 115-120.

Riddiford-Harland DL, Steele JR, Cliff DP, Okely AD, Morgan PJ, Baur LA. (2016) **Does participation in a physical activity program impact upon the feet of overweight and obese children?** J Sci Med Sport. 19(1): 51-55.

Riddiford-Harland DL, Steele JR, Storlien LH. (2000) **Does obesity influence foot structure in prepubescent children?** Int J Obes Relat Metab Disord. 24(5): 541-544.

Rodgers MM. (1988) **Dynamic biomechanics of the normal foot and ankle during walking and running**. Phys Ther. 68(12): 1822-1830.

Rosemann T, Grol R, Herman K, Wensing M, Szecsenyi J. (2008) **Association between obesity, quality of life, physical activity and health service utilization in primary care patients with osteoarthritis**. Int J Behav Nutr Phys Act. 5: 4.

Rozzi SL, Lephart SM, Gear WS, Fu FH. (1999) **Knee joint laxity and**

neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med. 27(3): 312-319.

Saghazadeh M, Kitano N, Okura T. (2015) **Gender differences of foot characteristics in older Japanese adults using a 3D foot scanner**. J Foot Ankle Res. 8: 29.

Santos DA, Silva AM, Baptista F, Santos R, Vale S, Mota J, Sardinha LB. (2012) **Sedentary behavior and physical activity are independently related to functional fitness in older adults**. Exp Gerontol. 47(12): 908-912.

Sarkar A, Singh M, Bansal N, Kapoor S. (2011) **Effects of obesity on balance and gait alterations in young adults**. Indian J Physiol Pharmacol. 55(3): 227-233.

Scott G, Menz HB, Newcombe L. (2007) **Age-related differences in foot structure and function**. Gait Posture. 26(1): 68-75.

Segal NA, Boyer ER, Teran-Yengle P, Glass NA, Hillstrom HJ, Yack HJ. (2013) **Pregnancy leads to lasting changes in foot structure**. Am J Phys Med Rehabil. 92(3): 232-240.

Shibuya N, Jupiter DC, Ciliberti LJ, VanBuren V, La Fontaine J. (2010) **Characteristics of adult flatfoot in the United States**. J Foot Ankle Surg.

49(4): 363-368.

Shields M, Tremblay MS, Connor Gorber S, Janssen I. (2012) **Abdominal obesity and cardiovascular disease risk factors within body mass index categories**. Health Rep. 23(2): 7-15.

Shultz SP, Sitler MR, Tierney RT, Hillstrom HJ, Song J. (2012) **Consequences of pediatric obesity on the foot and ankle complex**. J Am Podiatr Med Assoc. 102(1): 5-12.

Snow RE, Williams KR, Holmes GB. (1992) **The effects of wearing high-heeled shoes on pedal pressure in women**. Foot Ankle Int. 13(2): 85-92.

Song J, Kane R, Tango DN, Veur SS, Furmato J, Komaroff E, Foster GD. (2015) **Effects of weight loss on foot structure and function in obese adults: a pilot randomized controlled trial**. Gait Posture. 41(1): 86-92.

Spink MJ, Fotoohabadi MR, Wee E, Hill KD, Lord SR, Menz HB. (2011) **Foot and ankle strength, range of motion, posture, and deformity are associated with balance and functional ability in older adults**. Arch Phys Med Rehabil. 92(1): 68-75.

Spyropoulos P, Pisciotta JC, Pavlou KN, Cairns MA, Simon SR. (1991)

Biomechanical gait analysis in obese men. Arch Phys Med Rehabil. 72(13): 1065-1070.

Stacoff A, Nigg BM, Reinschmidt C, van den Bogert AJ, Lundberg A, Stüssi E, Denoth J. (2000) **Movement coupling at the ankle during the stance phase of running**. Foot Ankle Int. 21(3): 232-239.

Subotnick S. (1981) **The flat foot**. Phys Sports Med. 9(8): 85-91.

Subotnick SI. (1985) **The biomechanics of running. Implications for the prevention of foot injuries**. Sports Med. 2(2): 144-153.

Suzuki K, Ando J. (2014) **Genetic and environmental structure of individual differences in hand, foot, and ear preferences: A twin study**. Laterality. 19(1): 113-128.

Takao M, Komatsu F, Oae K, Miyamoto W, Uchio Y, Ochi M, Matsushita T. (2007) **Proximal oblique-domed osteotomy of the first metatarsal for the treatment of hallux valgus associate with flat foot: effect to the correction of the longitudinal arch of the foot**. Arch Orthop Trauma Surg. 127(8): 685-690.

Tanaka H, Kakiyama T, Takahara K, Yamauchi M, Tanaka M, Sasaki J, Taniguchi T, Matsuo H, Shindo M. (1995) **The association among fat distribution,**

physical fitness, and the risk factors of cardiovascular disease in obese women. Obes Res. 3 Suppl 5: 649S-653S.

Tanaka K, Okura T, Shigematsu R, Nakata Y, Lee DJ, Wee SW, Yamabuki K. (2004) **Target value of intraabdominal fat area for improving coronary heart disease risk factors**. Obes Res. 12(4): 695-703.

Tanamas SK, Wluka AE, Berry P, Menz HB, Strauss BJ, Davies-Tuck M, Proietto J, Dixon JB, Jones G, Cicuttini FM. (2012) **Relationship between obesity and foot pain and its association with fat mass, fat distribution, and muscle mass**. Arthritis Care Res (Hoboken). 64(2): 262-268.

Telfer S, Woodburn J. (2010) **The use of 3D surface scanning for the measurement and assessment of the human foot**. J Foot Ankle Res. 3(1): 1.

Teyhen DS, Stoltenberg BE, Collinsworth KM, Giesel CL, Williams DG, Kardouni CH, Molloy JM, Goffar SL, Christie DS, McPoil T. (2009) **Dynamic plantar pressure parameters associated with static arch height index during gait**. Clin Biomech (Bristol, Avon). 24(4): 391-396.

Tomassoni D, Traini E, Amenta F. (2014) **Gender and age related differences in foot morphology**. Maturitas. 79(4): 421-427.

Trudelle-Jackson E, Jackson AW, Morrow JR, Jr. (2011) **Relations of meeting national public health recommendations for muscular strengthening activities with strength, body composition, and obesity: the Women's Injury Study**. Am J Public Health. 101(10): 1930-1935.

Tsiros MD, Coates AM, Howe PR, Grimshaw PN, Walkley J, Shield A, Mallows R, Hills AP, Kagawa M, Shultz S, Buckley JD. (2013) **Knee extensor strength differences in obese and healthy-weight 10-to 13-year-olds**. Eur J Appl Physiol. 113(6): 1415-1422.

Umeki Y. (1991) **Static results of medial foot arch**. Nihon Seikeigeka Gakkai Zasshi. 65(10): 891-901.

Villarroya MA, Esquivel JM, Tomas C, Moreno LA, Buenafe A, Bueno G. (2009) **Assessment of the medial longitudinal arch in children and adolescents with obesity: footprints and radiographic study**. Eur J Pediatr. 168(5): 559-567.

Wang JK, Lee DH, Jang SH, Lee KH, Park SB. (2004) **The relationship between body mass index and foot parameters**. J Korean Acad Rehabil Med. 28(6): 606-612.

Wearing SC, Grigg NL, Lau HC, Smeathers JE. (2012) **Footprint-based estimates of arch structure are confounded by body composition in adults**. J Orthop Res.

30(8): 1351-1354.

Wearing SC, Hennig EM, Byrne NM, Steele JR, Hills AP. (2006) **Musculoskeletal disorders associated with obesity: a biomechanical perspective**. Obes Rev. 7(3): 239-250.

Wearing SC, Hills AP, Byrne NM, Hennig EM, McDonald M. (2004) **The arch index: a measure of flat or fat feet?** Foot Ankle Int. 25(8): 575-581.

Weiss EP, Racette SB, Villareal DT, Fontana L, Steger-May K, Schechtman KB, Klein S, Ehsani AA, Holloszy JO, Washington University School of Medicine CG. (2007) **Lower extremity muscle size and strength and aerobic capacity decrease with caloric restriction but not with exercise-induced weight loss**. J Appl Physiol (1985). 102(2): 634-640.

WHO. (2015) **Obesity and overweight**. http://www.who.int/mediacentre/factsheets/fs311/en/.

Wiklund P, Toss F, Weinehall L, Hallmans G, Franks PW, Nordstrom A, Nordstrom P. (2008) **Abdominal and gynoid fat mass are associated with cardiovascular risk factors in men and women**. J Clin Endocrinol Metab. 93(11): 4360-4366.

Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. (2002) **Proprioception and**

muscle strength in subjects with a history of ankle sprains and chronic instability. J Athl Train. 37(4): 487-493.

Williams DS, McClay IS. (2000) **Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity**. Phys Ther. 80(9): 864-871.

Williams DS, McClay IS, Hamill J. (2001) **Arch structure and injury patterns in runners**. Clin Biomech (Bristol, Avon). 16(4): 341-347.

Wunderlich RE, Cavanagh PR. (2001) **Gender differences in adult foot shape: implications for shoe design**. Med Sci Sports Exerc. 33(4): 605-611.

Zifchock RA, Davis I, Hillstrom H, Song J. (2006) **The effect of gender, age, and lateral dominance on arch height and arch stiffness**. Foot Ankle Int. 27(5): 367-372.

Zonfrillo MR, Seiden JA, House EM, Shapiro ED, Dubrow R, Baker MD, Spiro DM. (2008) **The association of overweight and ankle injuries in children**. Ambul Pediatr. 8(1): 66-69.

Research Achievement

Original Papers

1. Xiaoguang Zhao, Takehiko Tsujimoto, Bokun Kim, Kiyoji Tanaka. **Association of arch height with ankle muscle strength and physical performance in adult men.** Biology of Sport. 2017;34(2):119-126.

2. Xiaoguang Zhao, Takehiko Tsujimoto, Bokun Kim, Yasutomi Katayama, Kyousuke Wakaba, Zhennan Wang, Kiyoji Tanaka. **Effects of increasing physical activity on foot structure and ankle muscle strength in adults with obesity**. The Journal of Physical Therapy Science. 2016;28(8):2332-2336.

3. Xiaoguang Zhao, Takehiko Tsujimoto, Bokun Kim, Yasutomi Katayama, Kiyoji Tanaka. **Characteristics of foot morphology and their relationship to gender, age, body mass index and bilateral asymmetry in Japanese adults.** Journal of Back and Musculoskeletal Rehabilitation. 2016 (Preprint): 1-9.

Academic Conference Presentation

1. 趙暁光, 辻本健彦, 金甫建, 田中喜代次. **成人男性における足のアーチの高さが足関節筋力へ与える影響.** 日本介護福祉・健康づくり学会第 3 回大会, 東京, 2015.11.15.

2. Xiaoguang Zhao, Takehiko Tsujimoto, Bokun Kim, Yasutomi Katayama, Kiyoji Tanaka. **The effect of obesity on foot structure and ankle muscle strength.** The 6th Conference of Asia Society of Sports Biomechanics, Ningbo, China, 2016.10.13-16.

Acknowledgements

There are so many people to thank for helping and supporting me during my 3-year doctoral course. Without them, this thesis might not have been written successfully, and to whom I am greatly indebted.

First of all, I would like to appreciate Professor Tanaka Kiyoji for his guidance, patience and encouragement throughout my studying abroad in the University of Tsukuba. I also would like to thank Dr. Tsujimoto Takehiko and Dr. Kim Bokun for providing indispensable advice, information and support on different aspects of my project. Besides, I would like to thank all staffs in Tanaka Laboratory for assisting test and collecting data.

I would like to thank Dr. Katayama Yasutomi, Associate Professor of Faculty of Education, Kogakkan University. With the help of Dr. Katayama and his colleagues, I could collect data smoothly.

I also would like to acknowledge the Pigeon Company which provided a 3D foot scanner to the study, and Ms. Kaori Itagaki who guided me to operate the device.

Finally, I am sincerely grateful to my families and friends who always support me whether I am in adversity or in prosperity.